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PB-245 411

A QUANTITATIVE METHOD FOR EFFLUENT COMPLIANCE MONITORING RESOURCE ALLOCATION

SYSTEMS CONTROL, INCORPORATED

PREPARED FOR
ENVIRONMENTAL PROTECTION AGENCY

SEPTEMBER 1975

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/5-75-015

2.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE
A QUANTITATIVE METHOD FOR EFFLUENT COMPLIANCE MONITORING RESOURCE ALLOCATION

5. REPORT DATE
September 1975

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Arthur I. Cohen, Yaakov Bar-Shalom,
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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Systems Control, Inc.
1801 Page Mill Road
Palo Alto, California 94304

10. PROGRAM ELEMENT NO.
1HC619

11. CONTRACT/GRANT NO.
68-01-2232

12. SPONSORING AGENCY NAME AND ADDRESS
Office of Research and Development
U.S. Environmental Protection Agency
Washington, D.C. 20460

13. TYPE OF REPORT AND PERIOD COVERED
Final

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

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This report is submitted in fulfillment of Contract Number 68-01-2232 by Systems Control, Inc., under the sponsorship of the Office of Research and Development Environmental Protection Agency. Work was completed as of January 1975.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Wastewater Monitoring, Wastewater Standards, Effluent Monitoring, Water Quality Control, Effluent Compliance Monitoring, Resource Allocation, Statistical Analysis, Michigan Water Resources, Cost Effectiveness	Resource Allocation Program, Effluent Standards Compliance Monitoring	14A Methods and Equipment/ Cost Effectiveness

18. DISTRIBUTION STATEMENT UNLIMITED	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 259
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE 8.50

EPA Form 2220-1 (9-73)

EPA-600/5-75-015
September 1975

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EPA REVIEW NOTICE

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CONTENTS

Page

Abstract iii

List of Figures vi

List of Tables ix

Acknowledgements xii

Sections

I Conclusions 1

II Recommendations 2

III Introduction 4

IV Summary 7

V Statistical Characteristics of Effluent Streams 20

- V.1 Choice of Distribution 23
- V.2 Initial Statistical Distribution 46
- V.3 Update of Statistics 55

VI Cost of Undetected Violations 56

- VI.1 Effect on Ambient Quality Due to Effluent Loads 58
- VI.2 Damage Functions 66
- VI.3 Formulation of "Cost" of Undetected Violations 70

VII Resource Allocation Problem 84

- VII.1 Formulation of Problem 84
- VII.2 Method of Maximum Marginal Return 87

VIII Resource Allocation Program 94

- VIII.1 General Program Description 94
- VIII.2 Simplified Example 96
- VIII.3 Sensitivity Studies 104

IX Demonstration Project 122

- IX.1 Description of Data and Assumptions 122

CONTENTS (Cont'd)

Page

IX.2 Performance of Procedure 135

X References 144

XI Glossary 149

Appendices

A Estimates of Mean and Standard Deviation 153

B Investigation of the Correlation Between Effluent Constituents 164

C Expected Damage and Probability of Violation Calculation 169

D Resources Required to Monitor a Source 199

E Bayesian Update Formula 202

F Estimation of BOD-DO and COD-DO Transfer Coefficients and the Saturation Level of DO 205

G Data for Demonstration Project 210

FIGURES

No.		Page
4.1	Resource Allocation Program	9
4.2a	Example of Normal Density Function	12
4.2b	Example of Lognormal Density Function	13
4.3	Initial Allocation Table	15
4.4	Priority List of Samples	16
4.5a	Final Allocation Given Monetary Budget	17
4.5b	Final Allocation Given Maximum Allowed "Cost" of Undetected Violations	18
5.1	Example of Probability Density Function of pH	22
5.2	Kolmogorov-Smirnov Test for BOD Data	25
5.3	Kolmogorov-Smirnov Test for Suspended Solids (Dry Month)	25
5.4	Kolmogorov-Smirnov Test for Suspended Solids (Wet Month)	28
5.5	Kolmogorov-Smirnov Test for Coliform Data	28
5.6	(a) Histogram of Phosphate Concentration Data at Plant 144. (b) Normal. (c) Lognormal	32
5.7	(a) Frequency Distribution of Effluent Phosphate Daily Discharge at Plant 159, (b) Normal, (c) Lognormal	33
5.8	(a) Frequency Distribution of Effluent Chloride Ion Discharge at Plant 030, (b) Normal, (c) Lognormal	34
5.9	(a) Frequency Distribution of Effluent Chloride Ion Daily Discharge at Plant 144, (b) Normal, (c) Lognormal	35
5.10	(a) Frequency Distribution of Effluent Mercury Daily Discharge at Plant 144, (b) Normal, (c) Lognormal	36
5.11	(a) Frequency Distribution of Effluent Chloride Ion Concentration at Plant 144, (b) Normal, (c) Lognormal	37
5.12	(a) Frequency Distribution of Effluent Chloride Ion Daily Discharge at Plant 144, (b) Normal, (c) Lognormal	38

FIGURES (Cont'd)

No.		Page
5.13	Daily Samples of BOD Loadings From a Dry Month (Normal Assumption)	40 40
5.14	Daily Samples of BOD From a Dry Month (Lognormal Assumption)	40
5.15	Daily Samples of BOD Loadings From a Wet Month (Normal Assumption)	41
5.16	Daily Samples of BOD Loadings From a Wet Month (Lognormal Assumption)	41
5.17	Daily Samples of Suspended Solids Loadings From a Dry Month (Normal Assumption)	43
5.18	Daily Samples of Suspended Solids Loadings From a Dry Month (Lognormal Assumption)	43
5.19	Daily Samples of Suspended Solids Loadings From a Wet Month (Normal Assumption)	44
5.20	Daily Samples of Suspended Solids Loadings From a Wet Month (Lognormal Assumption)	44
5.21	Daily Samples of Coliform Loadings (Lognormal Assumption)	45
5.22	Initial Statistical Description Procedure	47
5.23	Example of Inclusion of Compliance Monitoring Information	53
6.1	Stream Characterization of Conservative Constituents	61
6.2	Stream Characterization of Non-Conservative, Non-Coupled Constituents	63
6.3	Example Damage Function	69
6.4	Example of Density Function for Suspended Solids	78
6.5	Example of Density Function for BOD_5	79
6.6	Density Function and Damage Function for Concentration of Suspended Solids in Stream	81

FIGURES (Cont'd)

No.		Page
6.7	Density Function and Damage Function for Concentration of Dissolved Oxygen in Stream	82 82
8.1	Flow of Resource Allocation Program	95
8.2	Resource Allocation Program	97
A.1.1	Plot of Equation (A.1.18)	156
A.2.1	Maximum Likelihood Estimate of Standard Deviation from Mean and Maximum in Lognormal Case	160
C.2.1	Example of Probability Density Function of pH	179
C.2.2	Damage Function for pH and pOH	182
F.1	Dissolved Oxygen Response as a Function of Water Body Type and ϕ Note: ($\phi = K_a/K_d$)	206
F.2	(K_a/K_d) as a Function of Depth	207
F.3	Dissolved Oxygen Saturation Versus Temperature and Chlorides	209

TABLES

No.		Page
5.1	Critical Values, $d_\alpha(N)$, of the Maximum Absolute Difference Between Sample and Population Cumulative Distributions [3]	26
5.2	Description of Example Cases	30
5.3	Example of Aggregation of Data	49
6.1	Behavior of Water Constituents	60
6.2	Damage Functions	68
6.3	Example Parameters	77
6.4	"Cost" Versus Number of Samples for Example	83
7.1	"Cost" of Undetected Violations and Priority Ordering	90
7.2	Priority List of Sources Sampled and Performance as Function of Total Resources	91
7.3	Allocation of Additional Increments of Resources to a Given Monitoring System	93
8.3	(a) Self Monitoring Data for Source 1, (b) Self Monitoring Data for Source 2, (c) Self Monitoring Data for Source 3, (d) Self Monitoring Data for Source 4, Pipe 1, (e) Initial Statistics for Source 4, Pipe 2	99
8.4	(a) Initial Statistics for Source 1, (b) Initial Statistics for Source 2, (c) Initial Statistics for Source 3, (d) Initial Statistics for Source 4, Pipe 1, (e) Self Monitoring Data for Source 4, Pipe 2	101
8.5	Expected Damage and Probability of Violation	103
8.6	Resources Needed to Sample	105
8.7	Priority List of Samples for Simplified Example	106
8.8	Final Allocation Given Monetary Budget	107
8.9	Final Allocation Given Maximum Allowed Cost of Undetected Violations	107

TABLES (Cont'd)

No.		Page
8.10	Priority List, Constituents in Source 3 All Normally Distributed	109
8.11	Priority List, Source 2 Constituents Correlated	110
8.12	Priority List, Sources' Constituents All Correlated	112
8.13	Priority List, Minimize Number of Undetected Violations	113
8.14	Effect of Discounting Past Data	114
8.15	Compliance Data - Source 2, Month 3	115
8.16	Initial Statistics for Source 2 with Compliance Monitoring Data: (a) $\gamma = 2$, (b) $\gamma = 4$	116
8.17	Expected Damage and Probability of No Violations for Source 2	117
8.18	Cases Considered for Sensitivity Study of Upstream Concentration	119
8.19	Comparison of Expected Damage for Various Assumed Upstream Concentrations	120
8.20	Priority Lists, Various Assumed Upstream Concentrations	121
9.1	Description of Effluent Sources	123
9.2	Resources Required to Monitor the Sources	129
9.3	Data for Demonstration Project, Case I	131
9.4	Priority List: Demonstration Project, Case I	133
9.5	Sampling Frequencies: Demonstration Project, Case I	134
9.6	Data for Demonstration Project, Case II	135
9.7	Priority List: Demonstration Project, Case II	136
9.8	Sampling Frequencies: Demonstration Project, Case II	137
9.9	Sampling Frequencies Before and After Interrupt: Demonstration Project, Case III	139
9.10	Observed Frequency of Violation and Average Damage	142

TABLES (Cont'd)

No.		Page
9.11	Performance Comparison	143
A.3.1	Relative Efficiency of Midrange as an Estimate of μ	161
A.3.2	C_N Versus N	162
A.3.3	Relative Efficiency of the Estimate $\hat{\sigma}$	163
B.1.1	Uncorrelatedness Test for N=30 Samples	165
B.2.1	Sample Correlations of the Measurements	167
B.2.2	Sample Correlations of Logs of the Measurements	167
C.2.1	Damage Function Breakpoints	181
D.1	Total Field and Office Costs	200
D.2	Laboratory Costs	201

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of a number of individuals that aided in the development of this report. In particular, recognition is given to the continuing support and guidance provided by the Project Officer, Mr. Donald H. Lewis of the Washington Environmental Research Center, Environmental Protection Agency. From the professional staff of Systems Control, Inc., Drs. Robert Larson, Robert Schainker, Harish Rao, and John Finnemore contributed many ideas to the original formulation of the methodology. Dr. Schainker also reviewed the draft manuscript and provided many suggestions helpful in finalizing this document. Special recognition also goes to Mr. Fred Morley, Mr. Fred Cowles, Mr. Richard Christianson and their associates at the Michigan Department of Natural Resources, for their time and support in providing the data base used in the demonstration example.

SECTION I
CONCLUSIONS

A procedure has been developed which determines how often to sample effluent sources in a compliance monitoring program. The sampling frequencies depend on the probability each source will be in violation of its standards, as well as the environmental damage each source is expected to cause to the receiving waters.

The potential utility of the procedure was demonstrated using data from 30 industries and municipal treatment plants. The sources chosen by the procedure for monitoring with highest priority were shown to be those sources most likely to violate a standard and cause environmental damage.

The information produced by the priority setting procedure is applicable to many types of water quality studies. The statistical descriptions of the effluents can be used as inputs to water quality models. The environmental damage expected from a source and the probability that a source will be in violation of a standard can be useful in the setting of effluent standards in "water quality limited" reaches of a river basin. The examination of these quantities quickly tells the user which sources are expected to have a major effect on water quality. The sensitivity of these quantities to changes in the standards or loadings can also be quickly determined.

SECTION II

RECOMMENDATIONS

The priority setting procedure developed in this report should be implemented as a user-oriented computer program. Such a program would be of great benefit to the monitoring agencies in the setting of sampling frequencies. A handbook should also be developed to describe the procedure to non-statistically trained personnel.

Notwithstanding the above recommendation, there are certain studies that can serve to increase the procedure's usefulness:

1) Geographical Considerations. In a river basin, there will exist groups of effluent sources located in close proximity to each other. When monitoring one source of the group, it may be beneficial to monitor another, since the cost of monitoring the sources concurrently will be less than the cost of monitoring them at different times. It is suggested that the priority procedure be augmented to account for such geographical considerations.

2) Scheduling of Monitoring Visits. Given the sampling frequencies, the compliance monitor must schedule his inspection crews over the monitoring period. This can be a difficult and time consuming job, especially in large regions. It is suggested that a computer program be developed that schedules the monitoring visits taking into account manpower, equipment and geographical factors.

3) Statistical Analysis. The procedure developed in this report allows the user to choose between two statistical distributions to describe each constituent of each source. The user also can specify whether the constituents of a source are statistically correlated or uncorrelated. The sampling priorities established

by the procedure are sensitive to both of these choices. There has been, however, little study on an industry by industry basis as to either the distribution of or correlation between constituents. It is suggested that there be further study into these statistical considerations.

4) Allocation Criteria. In this report, two allocation criteria are specified: (A) "cost" of undetected violations and (B) number of undetected violators. Additional useful criteria can be specified within the framework of the present procedure. As examples, consider the following two criteria: (A') violation "cost" of undetected violators and (B') degree of violation due to undetected violators. (A) and (A') both attach a cost, as measured by a damage function, to the effect due to an effluent source's load on pollutant concentration in a stream. Criteria (A) attaches a "cost" to a pollutant even if it is not violating an effluent standard while (A') only considers "violation cost" (i.e., it is assumed that no damage is done to the environment if the standard is not violated). The rational for using (A') over (A) is that the monitor may only be interested in damage due to standard violations and not in damage per se.

(B') is a measure of the degree of violation expected from the sources in the monitoring region. Thus, under (B'), those sources who have highest probability of being violators and which are expected to have loads most over their standard will be sampled with highest priority while under (B) only the former condition is considered.

Since these criteria may be useful to the monitoring agency, it is suggested that the priority procedure should be extended to include these additional allocation criteria.

SECTION III
INTRODUCTION

The Federal Water Pollution Control Act Amendments of 1972 (PL 92-500) requires the establishment of effluent limitations for all point sources by July 1, 1977. The effluent limitations* are stated as conditions on discharge permits issued to all point sources under the National Pollution Discharge Elimination System (NPDES). The Environmental Protection Agency or the state is required to establish monitoring programs to ensure that the effluent sources are in compliance with the standards. There are three ways the monitoring agency obtains information concerning the compliance of the dischargers:

(1) Self-Monitoring. The source is required to monitor its effluent levels and periodically transmit these records to the monitoring agency.

(2) Compliance Monitoring. The monitoring agency visits the source to ensure that the self-monitoring is being properly executed and reported.

(3) Ambient Monitoring. The water quality monitoring of the receiving waters.

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*A distinction is often made between effluent limitation and effluent standard. In this report these words shall be used interchangeably to denote a restriction established by the appropriate regulatory authority on the quantities and/or concentrations of chemical or biological constituents of point source wastewater.

The self-monitoring reports are the principal source of compliance information used by monitoring agencies since the agency expense to acquire these data is minimal. Some check is, however, needed on the reliability of the self-monitoring data. The compliance monitoring program is set up to provide that check. The compliance program also has other purposes associated with the permit program, such as verifying that the plant processes described in the permit are correct, evaluating new waste removal equipment, reviewing progress toward scheduled pollution control activities, and monitoring to aid in preparing enforcement actions. The ambient monitoring is primarily used to determine water quality, discern trends in water quality, and evaluate the overall effectiveness of pollution control in a region. Under certain conditions, however, ambient monitoring may flag effluent irregularities unmeasured by other means. Through knowledge of the effluent sources that could contribute to the decline in ambient quality, action can be initiated against possible violators.

This report is concerned with that part of the compliance monitoring program that determines whether the sources are in compliance with the effluent standards. Since the monitoring agency has limited resources available for compliance monitoring, it is important that these resources be used in an efficient manner. In this report, a procedure is developed which determines how often to monitor each source in a region to obtain maximum benefit from the compliance monitoring program. The procedure utilizes information from self-monitoring, ambient monitoring, and past compliance monitoring reports.

There are two types of effluent standards that have been established under NPDES: (i) a monthly average and (ii) a daily maximum. A source is in violation if either the value of a daily composite measurement exceeds the maximum standard or the average of the daily composites, over the month, exceeds the average standard. In order to determine whether an effluent source is in violation of the average standard, it is necessary to make measurements over a large percentage of the month; while to determine if the maximum standard is violated, it is only necessary to determine if the standard was exceeded over a single day. Since compliance monitoring is costly to the monitoring agency and since most regions will contain many effluent sources, it is not expected, in general, that compliance monitoring resources will be available to determine whether the average standard is violated. Therefore, in this report compliance monitoring is limited to determining whether the maximum standard is violated.

The remainder of this report is organized as follows: Section IV contains a summary of the priority setting procedure developed in this report. Its purpose is to introduce the procedure to potential users. Section V develops a statistical characterization of effluent source constituents and discusses how to obtain the statistical description of the effluents that is required to initialize the priority procedure. A method is also presented which specifies how the effluent statistics can be updated as additional data become available. Section VI formulates the criterion to be optimized in the priority setting procedure, denoted the "cost" of undetected violations. Also presented in this section is a discussion of the relationship between ambient quality and effluent load. Section VII restates the priority setting problem in terms of an optimization problem and describes the method used to solve it. Section VIII gives an overall description of how all the components needed to obtain the monitoring frequencies interact and presents a simplified example showing the procedure's operation. Section IX demonstrates the priority procedure on a detailed example utilizing data supplied by the State of Michigan.

SECTION IV

SUMMARY

The purpose of this summary is to introduce the procedure developed in this report to potential users, that is, the compliance monitoring staff of the state or EPA effluent monitoring programs. This summary also describes the basic considerations used in the development of this procedure.

The procedure developed in this report sets priorities as to which sources should be monitored and with what frequency. The procedure determines the sampling frequencies so that those sources that have a high probability of violating their standards and that can be expected to cause large environmental damage will be sampled with high priority. The objective in allocating the monitoring resources then is to minimize the "cost" of undetected violations, or equivalently, the expected environmental damage that would result from undetected violations. The "cost" of undetected violations for an effluent source depends on

(1) The expected frequency of a standard violation
(2) The expected magnitude of the violation
(3) The toxicity of the pollutants
(4) The assimilative capacity of the receiving waters at the discharge points.

These quantities are determined from past compliance and self-monitoring reports, effluent standards, and knowledge of the receiving water characteristics and the nature of the pollutants.

The user, at his option, can specify another allocation criterion, namely, the number of undetected violators. This criterion depends on the expected frequency of a standard violation.

Both, the "cost" of undetected violations and number of undetected violators assume that if the monitoring agency catches a violator once in the monitoring period, this component of compliance monitoring has done its job. At this point, it is up to the user to specify any follow-up actions (e.g., the monitor could elect to stay at the violator's site for a longer period or specify a given number of further visits during the monitoring period).

RESOURCE ALLOCATION PROGRAM

The basic flow of the procedure, denoted the Resource Allocation Program, is given in Figure 4.1. The various components are briefly described below

(1) Initialize Statistical Description

Combine the self-monitoring and compliance monitoring data to obtain an initial statistical description for each pollutant of each source.

(2) Calculate Expected Damage and Probability of Violation

Use the statistical description of the effluent loads, the effluent standards, and the stream parameters to obtain, for each source, its expected environmental damage and its probability of violation of the standards.

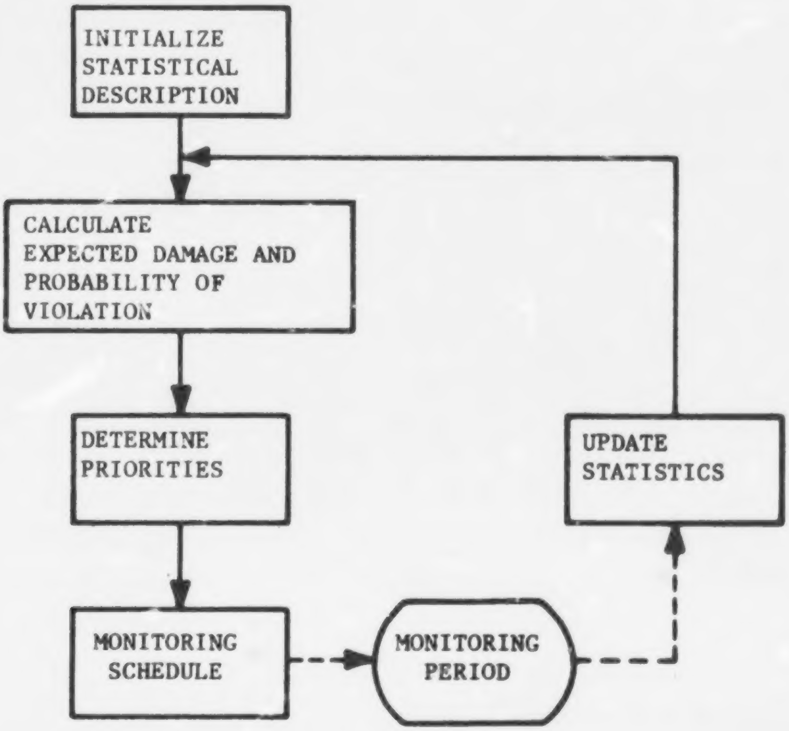
INITIALIZE STATISTICAL DESCRIPTION
CALCULATE EXPECTED DAMAGE AND PROBABILITY OF VIOLATION
DETERMINE PRIORITIES
MONITORING SCHEDULE
MONITORING PERIOD
UPDATE STATISTICS

Figure 4.1 Resource Allocation Program.

(3) Determine Priorities

Allocate the monitoring resources to minimize the "cost" of undetected violations.

(4) Monitoring Schedule

Take the sampling frequencies obtained in the previous component and determine which day of the monitoring period to sample which sources.

(5) Monitoring Period

This component represents the actual time spent monitoring the sources.

(6) Update Statistics

Combine new self-monitoring and compliance data with the initial statistics to obtain an updated statistical description of the effluents for use in the next monitoring period allocation.

This procedure has been implemented as a computer program to minimize the need for data handling and hand calculations. In the remainder of this section, several of the components of the Resource Allocation Program are described in more detail.*

Initialize Statistical Description

The daily composite value of each constituent of each source for which there is a standard is modeled by a probability density function or frequency distribution. The area under the density function between any two values of effluent specifies the fraction of the time the output of the source is between those two values. The area under the density function from zero to infinity is, clearly, always one. By allowing two types of density functions, normal and lognormal, a wide range of effluent loadings can be modeled with sufficient accuracy for determining sampling priorities. The normal density function is the standard "bell-shaped" frequency distribution. An effluent load is distributed with a lognormal distribution if the logs of the effluent values have a normal density function. Examples of a normal and lognormal density functions are shown in Figures 4.2a and 4.2b. Both the normal and lognormal density functions are parameterized by two parameters, a mean and a standard deviation. (For the lognormal case the mean and standard deviation are of the logs of the effluent values.) These parameters are obtained for each constituent of each source from the self-monitoring and compliance monitoring data. The parameters are then fed into the next stage of the Resource Allocation Program.

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*For a description of the theoretical foundations of this procedure, refer to Sections V through VIII.

Calculate Expected Damage and Probability of Violation

The monitoring frequencies depend on the environmental damage each source is expected to cause and the probability that each source is in violation of its standards. The environmental damage is related to the concentration of the water quality indicators in the receiving waters corresponding to the constitutents of the effluent. A value from 0 to 10 is given to each value of concentration depending on the degree of damage to the environment; this relationship is subjective and can be changed to meet the requirements of the user. The expected damage due to the constituents is then found by calculating the concentration of the pollutants in the receiving waters due to the source load, and then determining the environmental damage. The probability of violation of the daily standard for each constituent is simply the area under the constituent's density function to the right of the effluent standard. The environmental damage due to all the constituents from a source is the maximum of the damages due to each of the constituents, since water quality is typically limited by the pollutant causing the most damage. The probability of any of the constituents in the effluent exceeding its standard is a simple function of the probabilities that each individual constituent exceeds its standard. The expected damage and probability of violation of each source is fed into the next stage of the Resource Allocation Program.

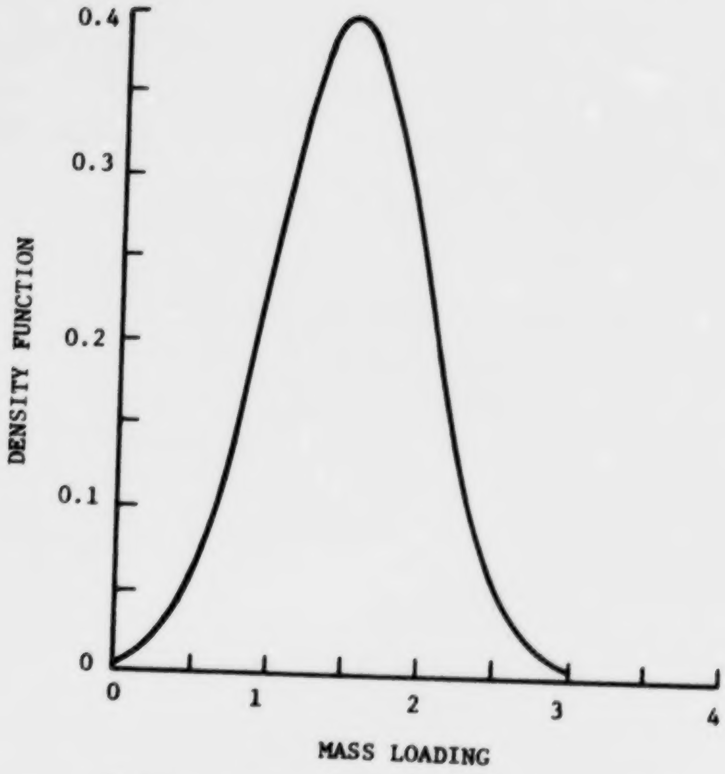

Figure 4.2a   Example of normal density function.

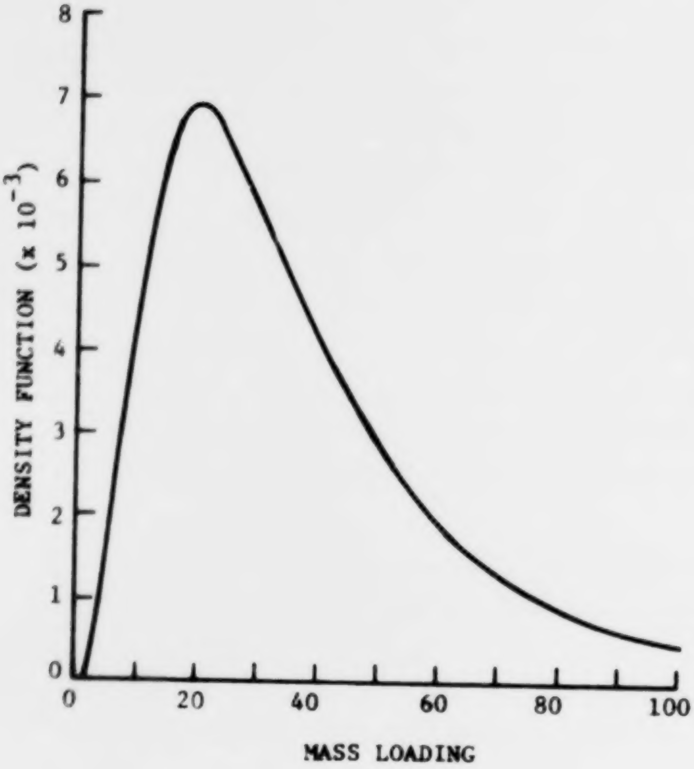

Figure 4.2b Example of lognormal density function.

Determine Priorities

The criterion for the priority setting procedure, the "cost" of undetected violations, is defined as the expected damage that would occur due to undetected violations. This function depends on the expected damage and probability of violation of each source. As a source is sampled more times, the "cost" of undetected violations for that source decreases since the probability decreases that the source will not be found in violation on any one of the visits. The priority procedure then allocates the monitoring resources to visit those sources where the marginal return (i.e. the decrease in "cost" per dollar spent) is greatest. Therefore, given a monitoring budget or a maximum allowed "cost" of undetected violations, the priority procedure specifies the frequency with which each source should be sampled in the monitoring period. It should be noted that the criterion can be easily altered to represent only the number of undetected violators. This is done by setting all the expected damages to one. In this case, the monitoring resources will be allocated to those sources whose decrease in the probability of not detecting a violation, per unit dollar, is greatest.

Examples of the output of this stage of the Resource Allocation Program, for a hypothetical example, are given in Figures 4.3, 4.4, and 4.5. Figure 4.3 gives the initial allocation of resources along with the resources used and the "cost" of undetected violations after allocating the samples. The initial allocation is based on subjective factors such as a desire to monitor sources of a certain size at least once, or a desire to monitor certain sources in a region where water quality is known to be bad. Figure 4.4 shows the marginal return and the decrease in "cost" of undetected violations as the resources are increased. The list is ordered by the marginal return, or equivalently by the priority of monitoring the sources. The first source on the list should be monitored with highest priority, the second source with next highest priority, etc. Thus, given a limit on total resources or a maximum allowed cost of undetected violations, Figure 4.4 contains all the information needed to obtain the priorities. Figures 4.5a and 4.5b show the "Final Allocation" table for this example. In Figure 4.5a a budget limit is given, while in Figure 4.5b a maximum "cost" of undetected violation is specified.

```
                    INITIAL ALLOCATION

     SOURCE                   TIMES SAMPLED     RESOURCES USED
--------------------------------------------------------------


1--JONES MANUFACTUR                 1                  535.50
2--SAFE CHEMICAL CO                 1                  548.00
3--SEWAGE TREATMENT                 1                  560.00
4--NUMBERNUM CO.                    1                  555.00

--------------------------------------------------------------

          TOTAL RESOURCES USED   2198.50
          COST OF UNDETECTED VIOLATIONS   4.27171
```

Figure 4.3   Initial Allocation Table

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```
                          PRIORITY LIST OF SAMPLES

                                                      COST OF
                                       MARGINAL     UNDETECTED  RESOURCES
PRIORITY     SOURCE SAMPLED           RETURN X100   VIOLATIONS   REQUIRED
---------------------------------------------------------------------------


    1        1--JONES MANUFACTUR      .10774492      5.07571      535.50
    2        3--SEWAGE TREATMENT      .09326524      4.55342     1095.50
    3        3--SEWAGE TREATMENT      .07959130      4.10603     1655.50
    4        1--JONES MANUFACTUR      .06899248      3.73658     2191.00
    5        3--SEWAGE TREATMENT      .06843515      3.35334     2751.00
    6        3--SEWAGE TREATMENT      .05862177      3.02506     3311.00
    7        3--SEWAGE TREATMENT      .05021559      2.74365     3871.00
    8        4--NUMBERWUN CO.         .04526206      2.49264     4426.00
    9        1--JONES MANUFACTUR      .04417806      2.25607     4961.50
   10        3--SEWAGE TREATMENT      .04301486      2.01519     5521.50
   11        3--SEWAGE TREATMENT      .03684665      1.80885     6081.50
   12        3--SEWAGE TREATMENT      .03156296      1.63209     6641.50
   13        1--JONES MANUFACTUR      .02828861      1.48061     7177.00
   14        3--SEWAGE TREATMENT      .02703693      1.32920     7737.00
   15        3--SEWAGE TREATMENT      .02315992      1.19951     8297.00
   16        1--JONES MANUFACTUR      .01811409      1.10251     8832.50
   17        1--JONES MANUFACTUR      .01159902      1.04039     9368.00
   18        1--JONES MANUFACTUR      .00742722      1.00062     9903.50
   19        4--NUMBERWUN CO.         .00590254       .96786    10458.50
   20        2--SAFE CHEMICAL CO      .00556719       .93735    11006.50
   21        1--JONES MANUFACTUR      .00475508       .91168    11542.00
   22        2--SAFE CHEMICAL CO      .00412025       .88931    12090.00
   23        2--SAFE CHEMICAL CO      .00304938       .87260    12638.00
   24        1--JONES MANUFACTUR      .00304534       .85629    13173.50
   25        2--SAFE CHEMICAL CO      .00225683       .84392    13721.50
   26        1--JONES MANUFACTUR      .00195003       .83348    14257.00
   27        2--SAFE CHEMICAL CO      .00167027       .82432    14805.00
   28        2--SAFE CHEMICAL CO      .00123616       .81755    15353.00
   29        2--SAFE CHEMICAL CO      .00091488       .81254    15901.00
   30        4--NUMBERWUN CO.         .00076974       .80826    16456.00
   31        2--SAFE CHEMICAL CO      .00067710       .80455    17004.00
   32        2--SAFE CHEMICAL CO      .00050112       .80181    17552.00
   33        2--SAFE CHEMICAL CO      .00037087       .79978    18100.00
   34        4--NUMBERWUN CO.         .00010038       .79922    18655.00
   35        4--NUMBERWUN CO.         .00001309       .79915    19210.00
   36        4--NUMBERWUN CO.         .00000171       .79914    19765.00
   37        4--NUMBERWUN CO.         .00000022       .79914    20320.00
   38        4--NUMBERWUN CO.         .00000003       .79914    20875.00
   39        4--NUMBERWUN CO.         .00000000       .79914    21430.00
   40        4--NUMBERWUN CO.         .00000000       .79914    21985.00

---------------------------------------------------------------------------
```

Figure 4.4 Priority List of Samples

```
                                  FINAL ALLOCATION

                                  BUDGET  10000.00

                          MIN NO. OF   MAX NO. OF
                          SAMPLES      SAMPLES       TIMES    RESOURCES    COST OF
SOURCE                    REQUIRED     ALLOWED       SAMPLED     USED      UNDETECTED
                                                                           VIOLATIONS
-----------------------------------------------------------------------------------


1--JONES MANUFACTUR          1            10            6      3213.00       .11058
2--SAFE CHEMICAL CO          1            10            1       548.00       .08687
3--SEWAGE TREATMENT          1            10           10      5600.00       .77476
4--NUMBERNUM CO.             1            10            1       555.00       .03767

-----------------------------------------------------------------------------------

        TOTAL RESOURCES USED  9916.00
        FINAL COST OF UNDETECTED VIOLATIONS   1.00988
```

Figure 4.5a   Final Allocation Given Monetary Budget

```
                                    FINAL ALLOCATION

                    MAXIMUM ALLOWED COST OF UNDETECTED VIOLATIONS   1.00000

                           MIN NO. OF   MAX NO. OF
                           SAMPLES      SAMPLES      TIMES     RESOURCES     COST OF
SOURCE                     REQUIRED     ALLOWED      SAMPLED      USED      UNDETECTED
                                                                            VIOLATIONS
------------------------------------------------------------------------------------------

1--JONES MANUFACTUR            1           10           7       3748.50       .07081
2--SAFE CHEMICAL CO            1           10           1        548.00       .08687
3--SEWAGE TREATMENT            1           10          10       5600.00       .77476
4--NUMBERWUN CO.               1           10           1        555.00       .03767
------------------------------------------------------------------------------------------

     TOTAL RESOURCES USED 10451.50
     FINAL COST OF UNDETECTED VIOLATIONS     .97011
```

Figure 4.5b Final Allocation Given Maximum Allowed "Cost" of Undetected Violations

Update Statistics

After monitoring the sources over the monitoring period, new compliance monitoring and self-monitoring data become available. These data are then used in determining the priorities for the next monitoring period. The statistical descriptions (i.e. mean and standard deviation) of the effluent constituents can be updated to include this new information. Upon updating the statistics, the compliance monitor is ready to repeat the priority setting procedure so as to obtain the sampling frequencies for the next monitoring period.

Detailed examples are presented in Sections VIII.2 and IX illustrating the use of the Resource Allocation Program.

SECTION V

STATISTICAL CHARACTERISTICS OF EFFLUENT STREAMS

The priority setting procedure for compliance monitoring requires that the daily composite effluent loads, due to their inherent variability, be modeled statistically. Among the questions that must be addressed in developing a statistical model are:

- What probability distributions adequately model the effluent data?
- What is the statistical correlation between the various constituents of the effluent from a source?
- What is the time-varying nature of the statistics?

Section V.1 shows, for several example sets of data, that the normal and lognormal distributions adequately model the statistics of the daily composite effluent loadings. In order to decide whether to model a particular constituent by a normal or lognormal distribution, it is necessary to process a large amount of daily data. It is not expected that the individual monitoring agency will have the resources to analyze the daily data of each source in its jurisdiction. It is only postulated that the monitoring agency will have a monthly mean and maximum for each constituent of each source in its jurisdiction. It is only postulated that the monitoring which distribution can be associated with a given industrial process. Since this information is unavailable at the publication of this report, several guidelines are specified on how to choose between the normal and lognormal cases.

The normal and lognormal distributions are parameterized by a mean and a standard deviation. (For the lognormal distribution, the mean and standard deviation are of the logs of the data.) Since it is only assumed that the monthly mean and maximum, and not the sample standard deviation, are available to the monitor, the standard deviation of the normal process has to be estimated using nonstandard estimation procedures. The situation is more complicated for the lognormal case, since neither the sample mean of the logs of the data nor the sample standard deviation of the logs of the data are available. Appendix A develops approximate maximum likelihood estimates of the mean and standard deviation from the sample mean and maximum of the data for both the normal and lognormal cases. These estimates are tested on real data in Section V.1 to show that they, coupled with the associated distributions, adequately describe the statistical variations. The case is slightly more complicated for pH. The data for pH available to the monitor will include a maximum and a minimum monthly value and possibly a mean monthly value. If a mean value is given, the pH can be modeled by a mean and two standard deviations - one based on the mean and the maximum, the other based on the mean and the minimum. The estimates of the standard deviations are based on the procedures just discussed. The resulting density function has a shape shown in Figure 5.1. If a mean is not given, the mean and a single standard deviation can be estimated from the minimum and the maximum. This estimation procedure is also given in Appendix A.

There has been little study into the statistical correlation of the constituents of an effluent. As with the problem of determining the appropriate distributions, it is not expected that the monitoring agency would be able to determine the correlation of the constituents of the sources in its jurisdiction. It is therefore necessary that the correlation coefficients be obtained from industry-wide studies. Since these are unavailable at the present time, it is assumed, unless other knowledge is available, that the constituents from a source are uncorrelated. The priority setting procedure also allows for the case where the constituents are completely correlated. In Appendix B, a correlation study for a single municipal treatment plant is carried out. It is clear that no general conclusions can be reached from the analysis of one water treatment plant. The analysis has shown the variability in the correlation parameters from month to month and the problems inherent in choosing

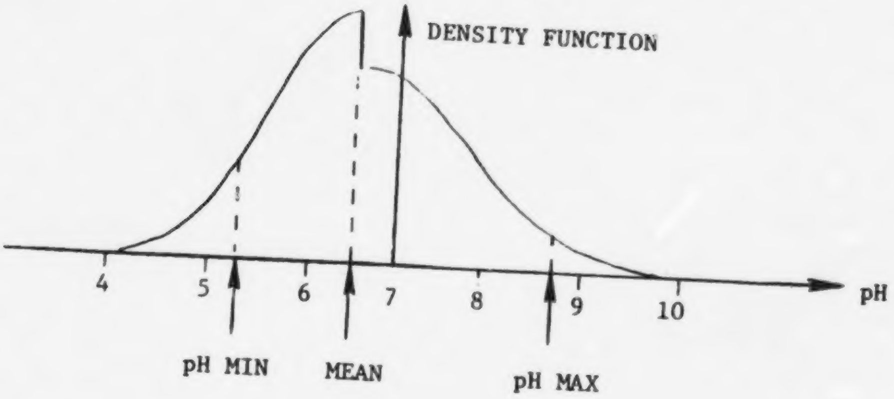

Figure 5.1 Example of probability density function of pH.

between the hypotheses of uncorrelated constituents and correlated constituents.

The time-varying nature of the statistics comes from two sources: (1) periodic variations due to weekly, monthly, or seasonal variations and (2) trends due to changes in the plant processes. The weekly and monthly variations are averaged out in the input data (i.e., monthly mean and maximum). These variations, if known, should be taken into account when determining when, in a monitoring period, to monitor a particular source. The seasonal variations and trends are taken into account in the statistical characterization by discounting past information and updating the statistics as new data become available.

The specific procedures used in the Resource Allocation Program to obtain the initial statistical description of the effluent sources and to update the statistics as new information becomes available are discussed in Sections V.2 and V.3 respectively.

V.1 CHOICE OF DISTRIBUTION

Testing for Distribution Acceptability

This subsection addresses the problem of what probability distribution or distributions are appropriate to describe the inherent variability of effluent constituents. Based upon previous studies [1], [2] as well as operational considerations (i.e., implementation feasibility), the normal and lognormal distributions have been chosen as candidates. A statistical testing procedure [3], namely the Kolmogorov-Smirnov (K-S) test, is used to test whether it is "acceptable" to consider the effluent data as being described by a certain probability distribution.

The statistical test whether to accept the "null hypothesis" (H_o), that the distribution is normal (or lognormal), is subject to a given probability of error of rejecting H_o when it is true. This probability of error, denoted α, is called the "level of significance" of the test.

If H_o is accepted when α, the allowed probability of incorrectly rejecting H_o, is large, then the probability that H_o is true is high. The Kolmogorov-Smirnov test compares the deviations of the empirical probability distribution from the assumed distribution. The smaller the largest observed deviation, the higher is the "significance" of the null hypothesis, i.e., that the observed variables come from the assumed distribution.

The Kolmogorov-Smirnov test will now be applied to Palo Alto Municipal Waste Treatment Plant data* to determine whether the normality or lognormality assumption can be accepted, and at what level of significance. The test is done on BOD, suspended solids, and coliform data.

The BOD data for July 1973 are considered first. A plot of the observed cumulative distribution and the normal distribution with the sample mean and sample variance appears in Figure 5.2. The distributions are plotted versus

$$\xi = \frac{x - \mu}{\sigma}$$

the deviation of the loading, x, from the mean, μ, normalized by the standard deviation, σ. In this case the sample mean and standard deviation are used. The solid line is the standard normal distribution, with zero mean and unit standard deviation. The points denoted by "▲" in the figure are the normalized deviations of the measurements from their mean and this is used to test the normality assumption. The lognormality assumption is tested by plotting the normalized deviations of the logs of the measurements from the mean of the logs (denoted "●" on Figure 5.2).

The K-S test determines whether the maximum deviation between the sample distribution and the assumed distribution exceeds the critical value for a given level of significance. The critical values, i.e., the maximum

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* Data obtained from Palo Alto Wastewater Treatment Plant Automation Project [4].

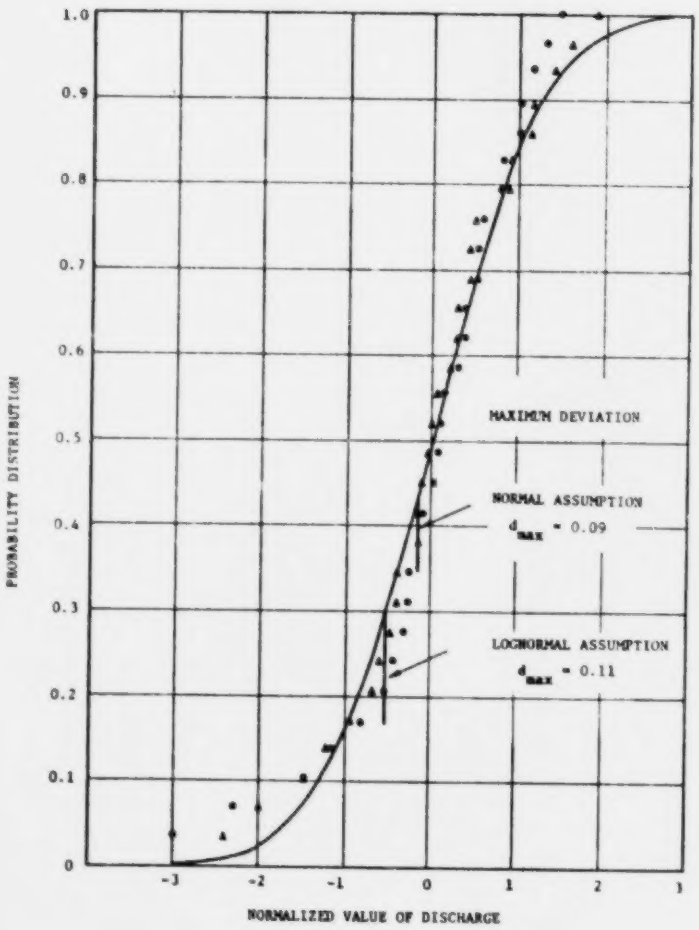

Figure 5.2 Kolmogorov-Smirnov test for BOD data.

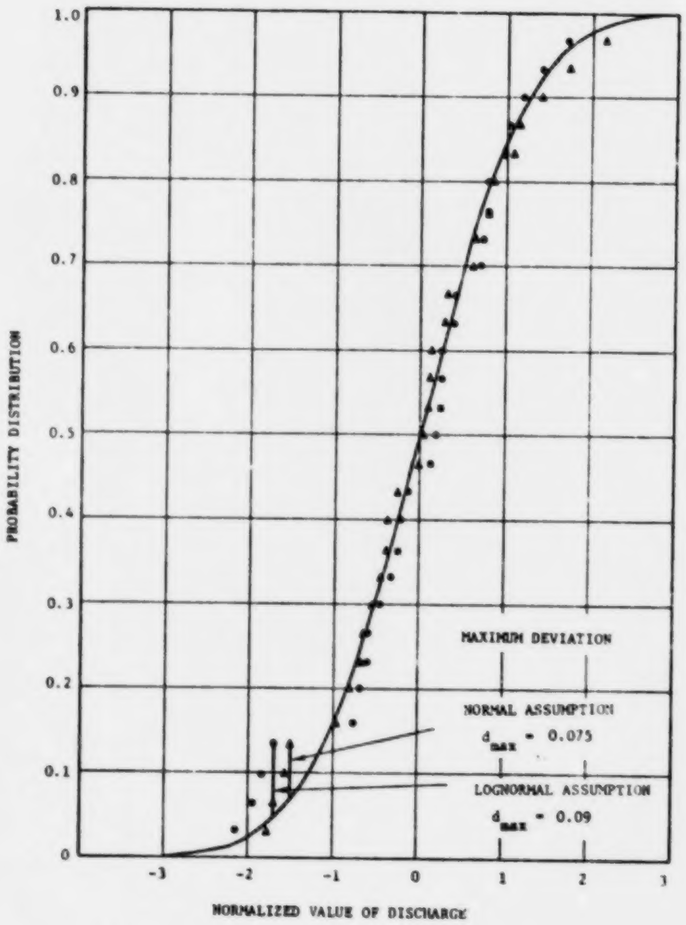

Figure 5.3 Kolmogorov-Smirnov test for suspended solids (dry month).

allowable deviation for a given level of significance for the Kolmogorov-Smirnov test, are shown in Table 5.1. The number of data points used for the plot of Figure 5.2 was 29 and, as can be seen, the maximum deviations are about 0.1 for both normal and lognormal assumptions. This shows that either of the hypotheses is acceptable at a level of significance over 20%, which is quite high.* In the statistical literature it has become customary to use 5% level of significance; thus in the present case the results are more significant than the customary required level for acceptance of H_o.

Table 5.1 CRITICAL VALUES, $d_\alpha(N)$, OF THE MAXIMUM ABSOLUTE DIFFERENCE BETWEEN SAMPLE AND POPULATION CUMULATIVE DISTRIBUTIONS [3].

Sample size (N)	Level of significance (α)				
	0.20	0.15	0.10	0.05	0.01
5	0.446	0.474	0.510	0.565	0.669
10	0.322	0.342	0.368	0.410	0.400
15	0.266	0.283	0.304	0.338	0.404
20	0.231	0.246	0.264	0.294	0.356
25	0.21	0.22	0.24	0.27	0.32
30	0.19	0.20	0.22	0.24	0.29
35	0.18	0.19	0.21	0.23	0.27
over 35	$\frac{1.07}{\sqrt{N}}$	$\frac{1.14}{\sqrt{N}}$	$\frac{1.22}{\sqrt{N}}$	$\frac{1.36}{\sqrt{N}}$	$\frac{1.63}{\sqrt{N}}$

---

*Since the empirical distribution is compared here to an assumed distribution with estimated rather than true parameters, the actual level of significance is somewhat lower (see Kendall and Stuart [3]).

In the case of the suspended solids data from a dry month presented in Figure 5.3, the largest deviation for both normal and lognormal assumptions are below 0.1. Therefore one can accept either of these assumptions at 20% level of confidence. For a wet month, the suspended solids data, as shown in Figure 5.4, exhibit a large deviation under the normal assumption, but this hypothesis is still acceptable at 15% level of significance; the lognormal assumption is accepted at a level of significance larger than 20%.

A set of 28 coliform measurements (Jan. 1974) are plotted in Figure 5.5 to test their distribution via the Kolmogorov-Smirnov method. Using Table 5.1 it can be seen that the normal assumption is rejected even at a low level of significance of 1%, while the lognormal assumption is accepted at a 15% level.

The conclusion is that, except for coliforms, the normal and lognormal hypotheses are both acceptable. For the coliform data the normal assumption is not adequate because of its rather large range of variability and the skewness of the frequency histogram.

Fitting of Distributions to Real Data

This subsection compares how well the following statistical assumptions fit the data.

(1) Normal distribution - mean equals sample mean and standard deviation equals sample standard deviation.

(2) Normal distribution - mean equals sample mean and standard deviation estimated from mean and maximum value (obtained with the procedure of Appendix A).

(3) Lognormal distribution - mean of logs equals sample mean of logs, standard deviation of logs equals sample standard deviation of logs.

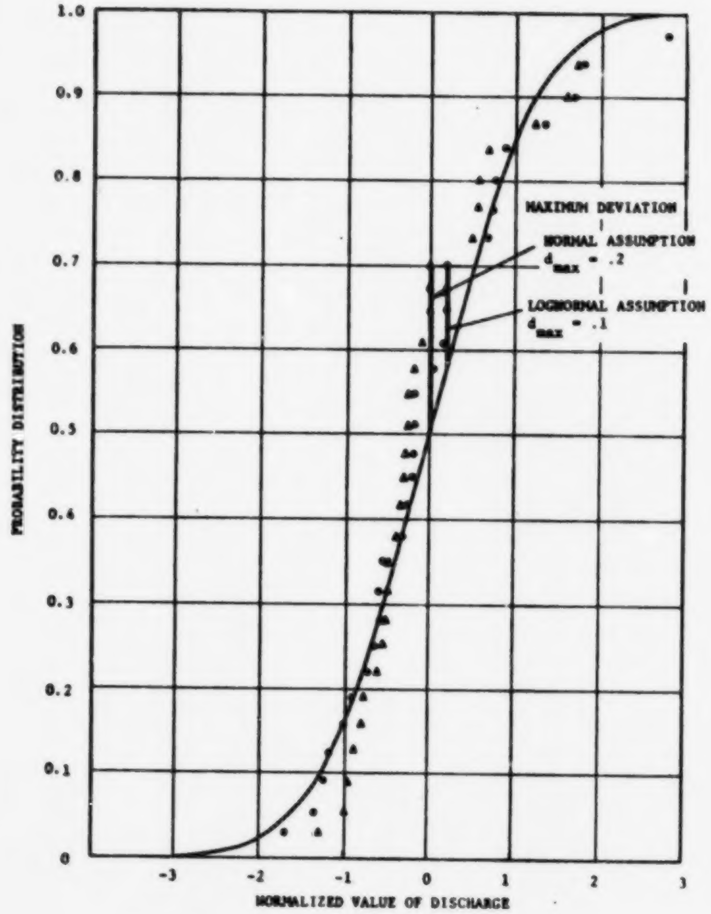

Figure 5.4 Kolmogorov-Smirnov test for suspended solids (wet month).

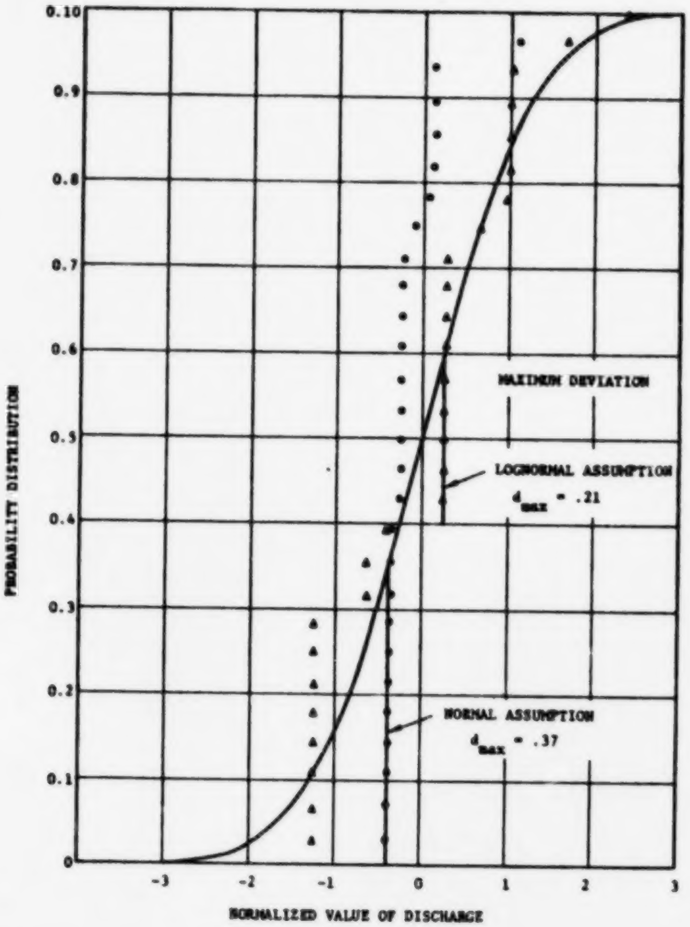

Figure 5.5 Kolmogorov-Smirnov test for coliform data.

(4) Lognormal distribution - mean of logs equals sample mean of logs, standard deviation of logs estimated from mean and maximum value of logs (obtained with the procedure of Appendix A).

To determine which distribution fits the data best, the data are plotted on normal probability paper. The normal distribution then appears as a straight line. The lognormal assumption is also a straight line if the distribution of the logs of the data is plotted. This technique was used, as opposed to the more sophisticated tests such as the K-S test, for the following reasons:

- It gives a simple visual test of the various assumptions.
- It can be easily used to determine if the data agree with the assumed distribution for large values of the constituent (i.e., at values where a violation or damage will occur).

This procedure is demonstrated on daily data of both effluent concentration and effluent loadings over either a six-month or twelve-month period for the non-fertilizer phosphorus chemicals industry and the inorganic chemicals, alkali, and chlorine industries [5], [6]. Table 5.2 describes the various cases and includes the sample mean, sample standard deviation, maximum and estimated standard deviation (from mean and maximum). (For the lognormal cases, the statistics are of the logs of the data.) The figures are distributions plotted on normal probability paper so that a normal process will lie close to a straight line. The data are normalized so that the sample mean equals zero and the sample standard deviation equals one. For each case, the following two normal distributions are compared: the means are equal to the sample mean for both cases; the standard deviation for one case is equal to the sample standard deviation, and for the other case, is equal to the estimated standard deviation from the sample mean and maximum. Figures 5.6a through 5.12a

Table 5.2 DESCRIPTION OF EXAMPLE CASES.

Figure	Plant #	Constituent	Time period (months)	Normal	Lognormal	Mean	Stan. dev.	Max	Est. stan. dev.
5.6b	159	PO_4 (ppm)	12	X		24.0	3.40	34.5	3.31
5.6c					X	1.38	.063	1.54	0.56
5.7b	159	PO_4 (kg/day)	12	X		235	54.6	370	48.0
5.7c					X	2.36	.110	2.57	.077
5.8b	030	Cl-ion (kg/day)	6	X		3060	1220	6450	1290
5.8c					X	3.44	2.21	3.81	2.14
5.9b	144	Hg (10^{-3} ppm)	6	X		3.78	2.05	10.5	2.55
5.9c					X	.511	.249	1.02	.194
5.10b	144	Hg (10^{-3} kg/day)	6	X		17.6	10.5	47.0	11.1
5.10c					X	1.16	.306	.167	.193
5.11b	144	Cl-ion (10^2 ppm)	6	X		6.50	6.80	29.5	8.7
5.11c					X	.544	.529	1.47	.352
5.12b	144	Cl-ion (10^3 kg/day)	6	X		3.26	3.47	16.5	5.00
5.12c					X	.267	.494	1.22	.360

show the corresponding histograms. From these histograms, we see that the density functions in Figures 5.6a, 5.7a, and 5.8a are of the normal shape, the density function is Figures 5.9a and 5.10a are somewhat of a normal shape, and the density functions in Figures 5.11a and 5.12a are far from normal. Examining the figures, the following conclusions can be drawn:

- The data in Figures 5.6, 5.7, and 5.8 fall closer to the normal (as opposed to lognormal) distribution. Good fit to the data is obtained, under the normal assumption, by using either estimate of the standard deviation.
- The data in Figures 5.9 and 5.10 are fit equally well by the normal or lognormal distributions. The fit to the data using the estimated standard deviation (from mean and maximum) is better for large values of the constituent than the fit obtained using the sample standard deviation.
- The data in Figures 5.11 and 5.12 fit the lognormal distribution better.

From these few examples, it is not possible to make any general statements assigning either normal or lognormal distributions to an industry or a constituent. However, the following tentative conclusions can be made:

- The normal and lognormal distributions with the standard deviation estimated from the mean and maximum give a good fit to the data for many cases.
- A better fit for large values of constituent is obtained when the standard deviation is estimated from the mean and maximum as opposed to using the sample standard deviation.

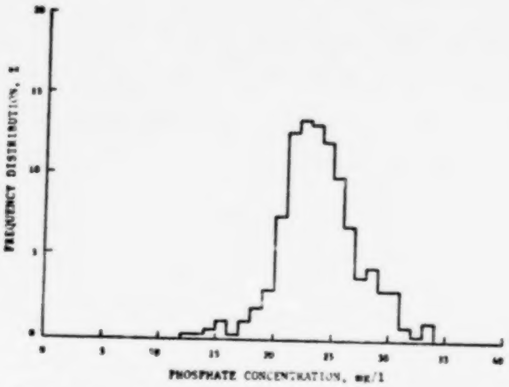

Figure 5.6a Histogram of phosphate concentration data at plant 144.

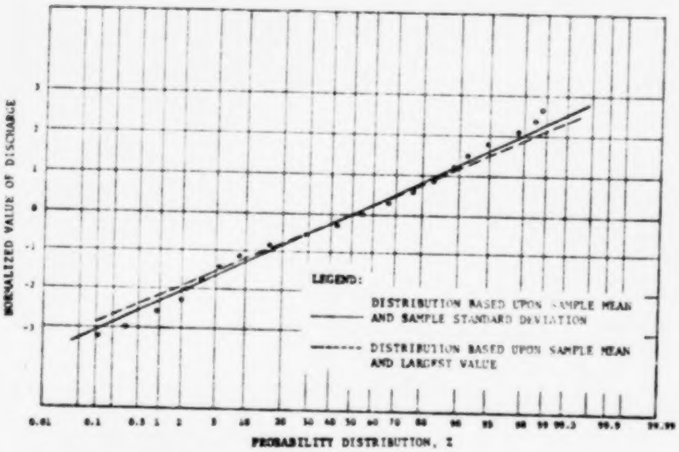

Figure 5.6b Normal.

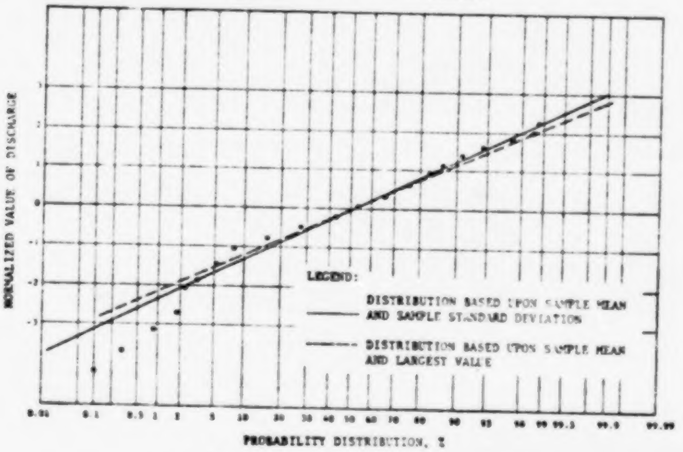

Figure 5.6c Lognormal.

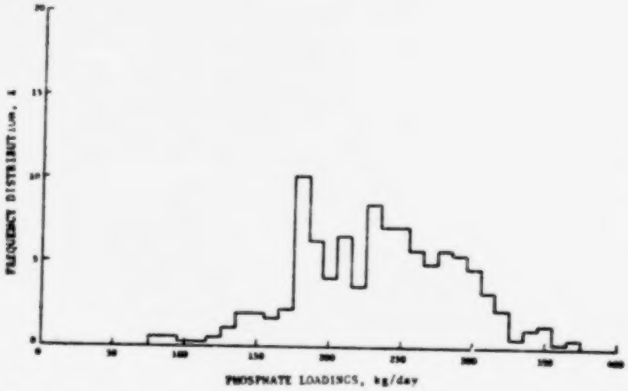

Figure 5.7a Frequency distribution of effluent phosphate daily discharge at plant 159.

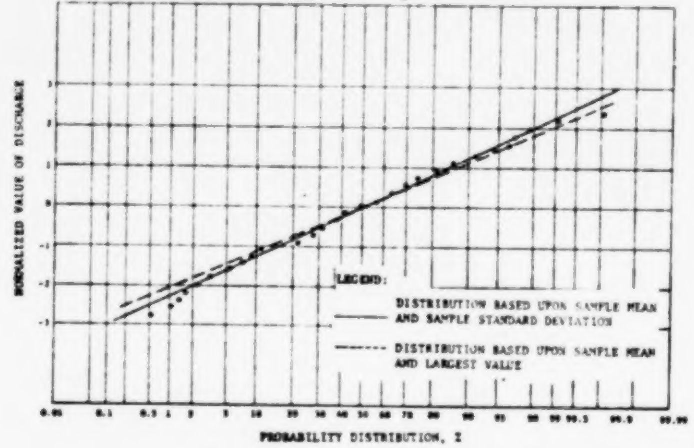

Figure 5.7b Normal.

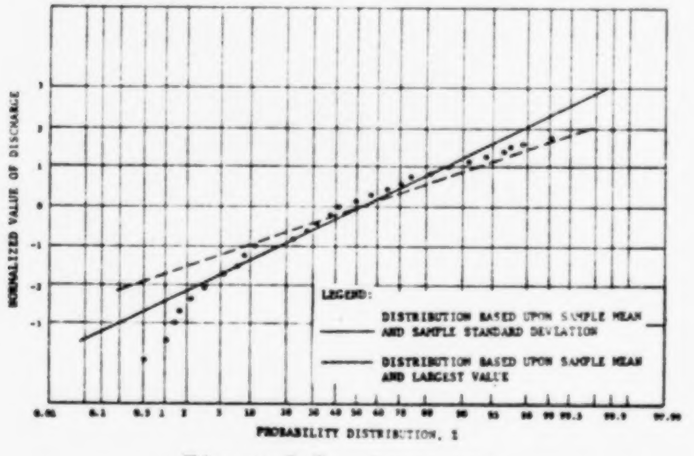

Figure 5.7c Lognormal.

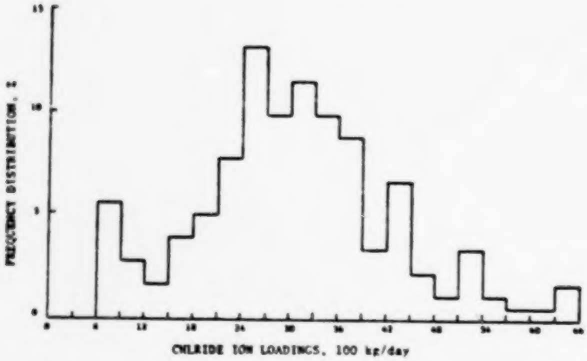

Figure 5.8a Frequency distribution of effluent chloride ion discharge at plant 030.

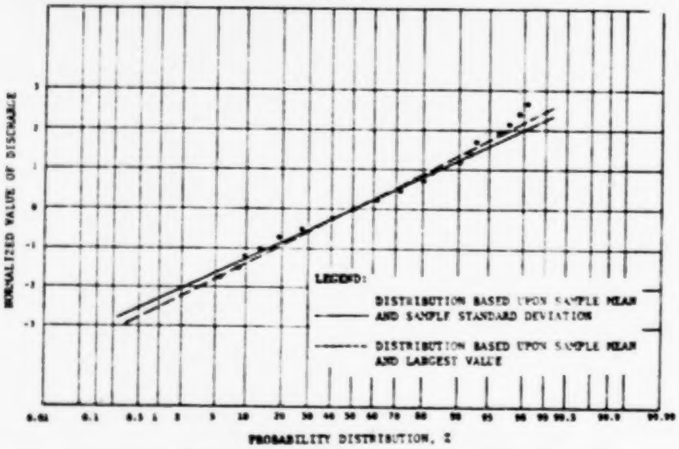

Figure 5.8b Normal.

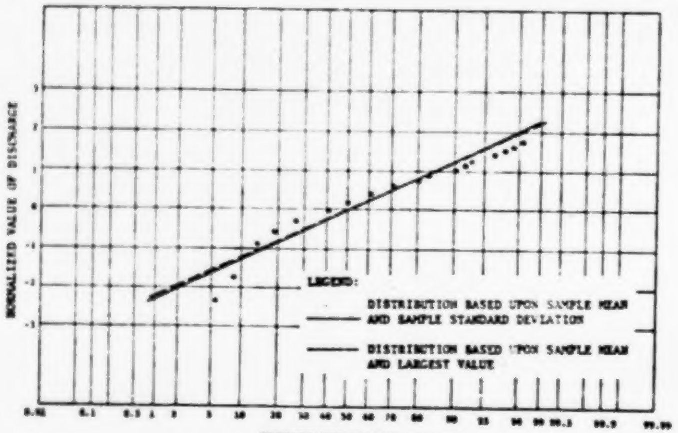

Figure 5.8c Lognormal.

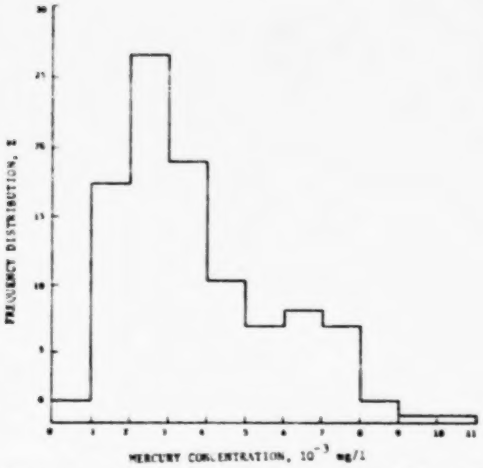

Figure 5.9a Frequency distribution of effluent chloride ion daily discharge at plant 144.

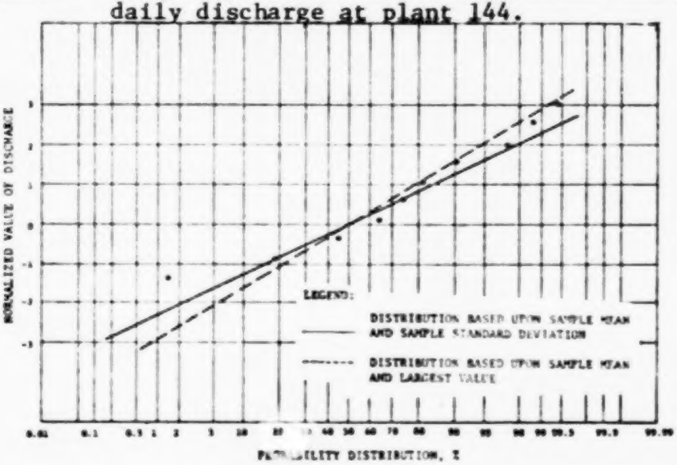

Figure 5.9b Normal.

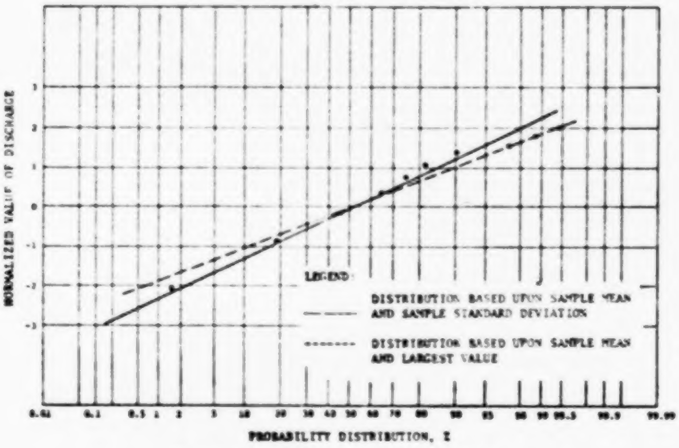

Figure 5.9c Lognormal.

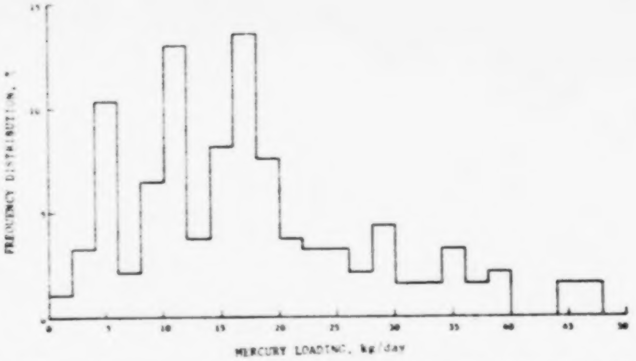

Figure 5.10a Frequency distribution of effluent mercury daily discharge at plant 144.

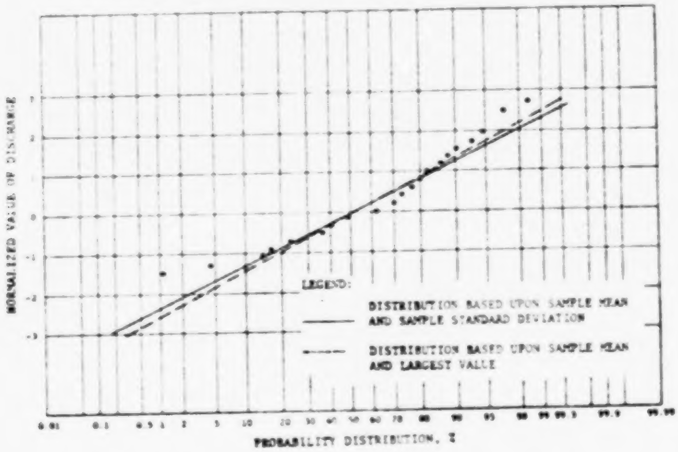

Figure 5.10b Normal.

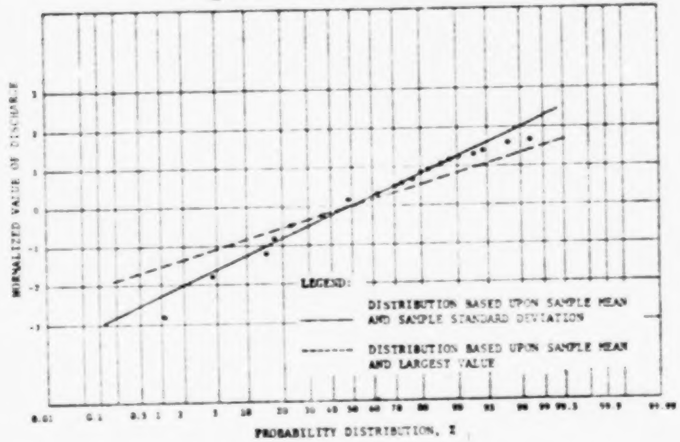

Figure 5.10c Lognormal.

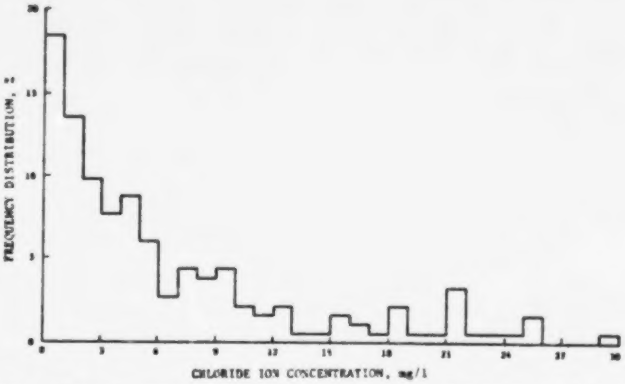

Figure 5.11a Frequency distribution of effluent chloride ion concentration at plant 144.

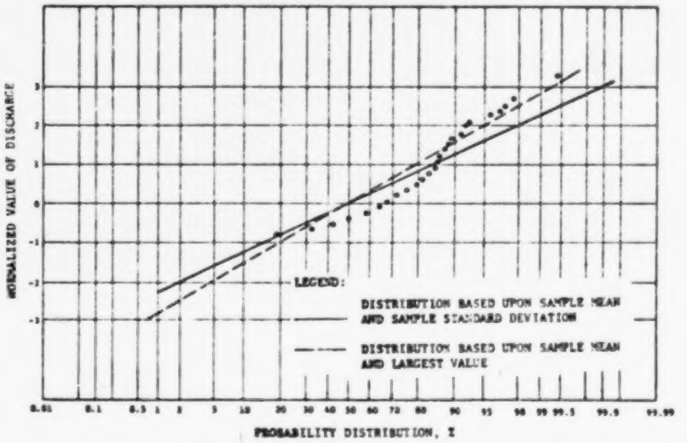

Figure 5.11b Normal.

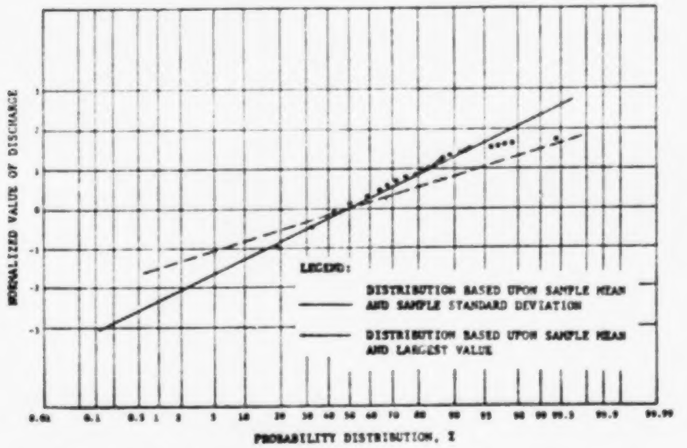

Figure 5.11c Lognormal.

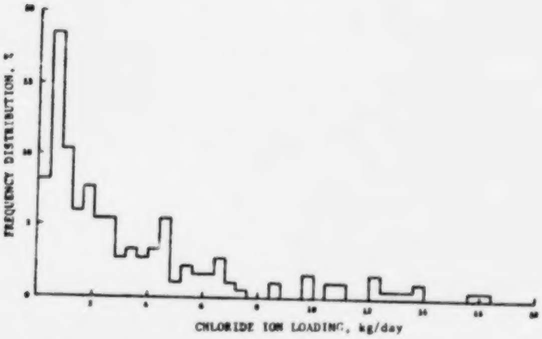

Figure 5.12a Frequency distribution of effluent chloride ion daily discharge at plant 144.

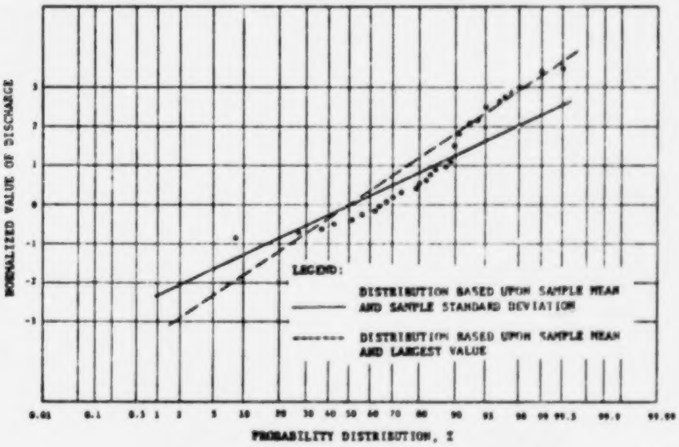

Figure 5.12b Normal.

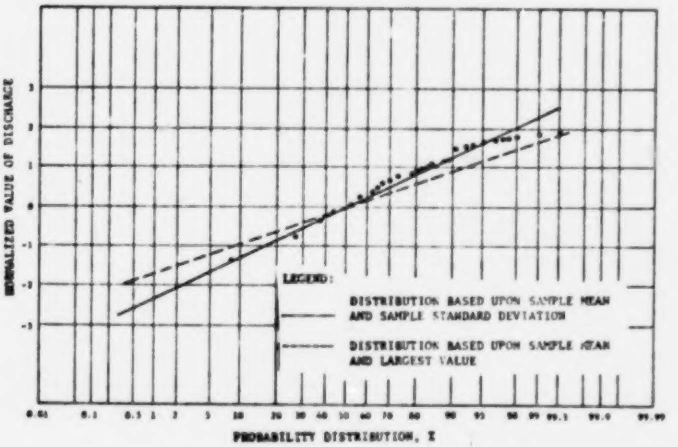

Figure 5.12c Lognormal.

Effect of Seasonal Variations on Distribution

Next an investigation of distribution properties of effluent pollutants, with emphasis on the possible effect of seasonality, is presented. The data used in this study were obtained from the Palo Alto Municipal Waste Treatment Plant [4].

A plot of the empirical distribution of the samples of BOD loadings from a dry month (July 1973) is presented in Figure 5.13. For convenience, they have been normalized, that is, their mean is zero and standard deviation is unity. The solid line represents the standard normal distribution and it appears (visually) to fit well. The normal distribution, using an estimate of the standard deviation from the maximum observed value (see Appendix A for the estimation procedure), is plotted with a broken line. The maximum likelihood estimate $\hat{\sigma}$ based on the largest observation (1.88 in this case) is

$$\hat{\sigma} = \frac{1.88}{\zeta} = \frac{1.88}{2.01} = 0.935$$

where the value of ζ was obtained from Figure A.1.1 of Appendix A, corresponding to the number of measurements $n = 29$. The two distributions are almost identical, and this illustrates the effectiveness of the estimation procedure developed in Appendix A.

The plot of the logs of the BOD loadings from the same dry month, also normalized as before appears in Figure 5.14. The fit to a normal distribution in the figure, which corresponds to the loadings being lognormally distributed, is not as good as in Figure 5.13; however, as discussed earlier, it is acceptable according to the Kolmogorov-Smirnov test. The broken line corresponds to the distribution with the standard deviation estimated according to the same method as above.

Plots of daily samples of BOD loadings for a wet month (November 1973) are given in Figures 5.15 and 5.16 under the normal and lognormal

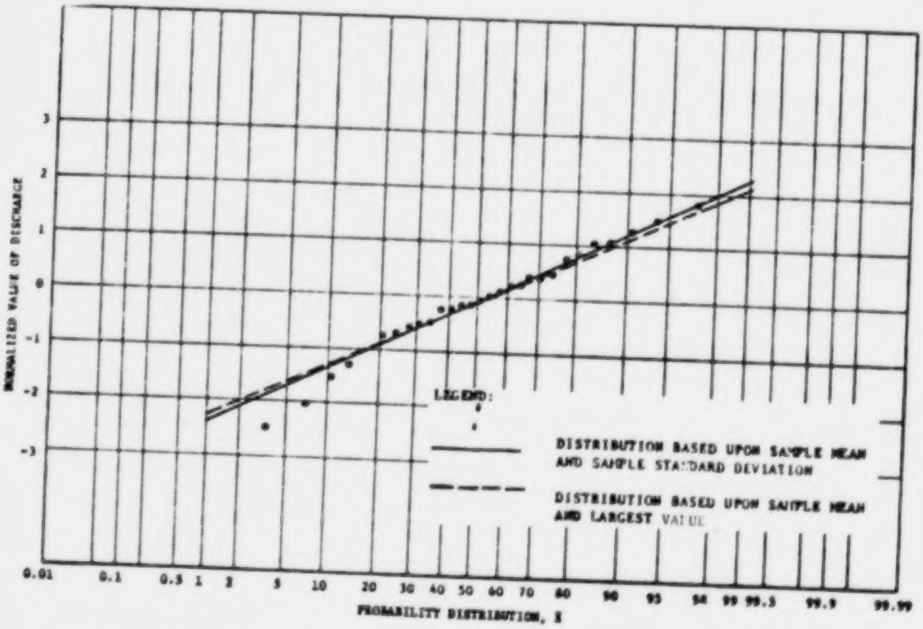

Figure 5.13 Daily samples of BOD loadings from a dry month (normal assumption).

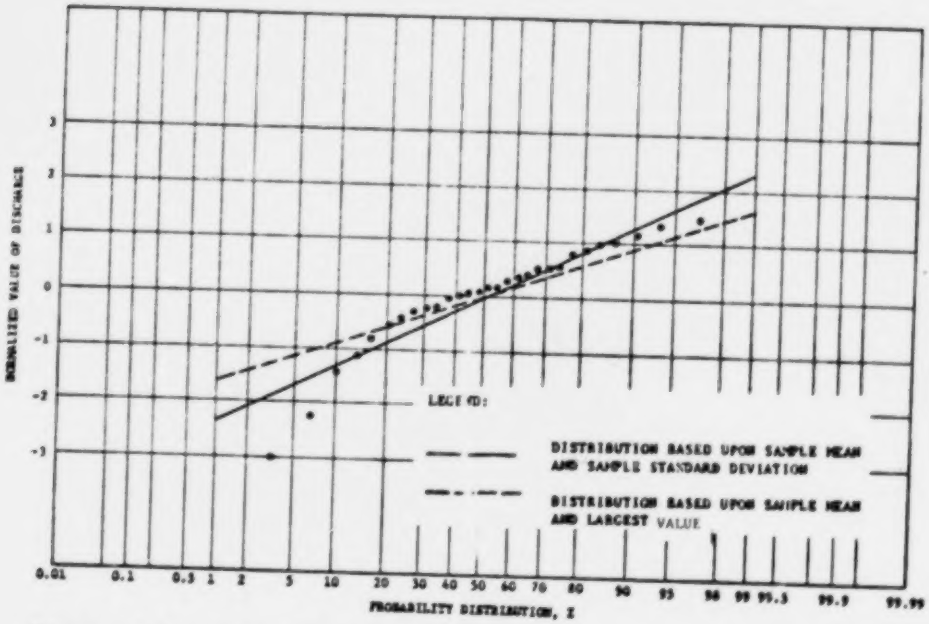

Figure 5.14 Daily samples of BOD from a dry month (lognormal assumption).

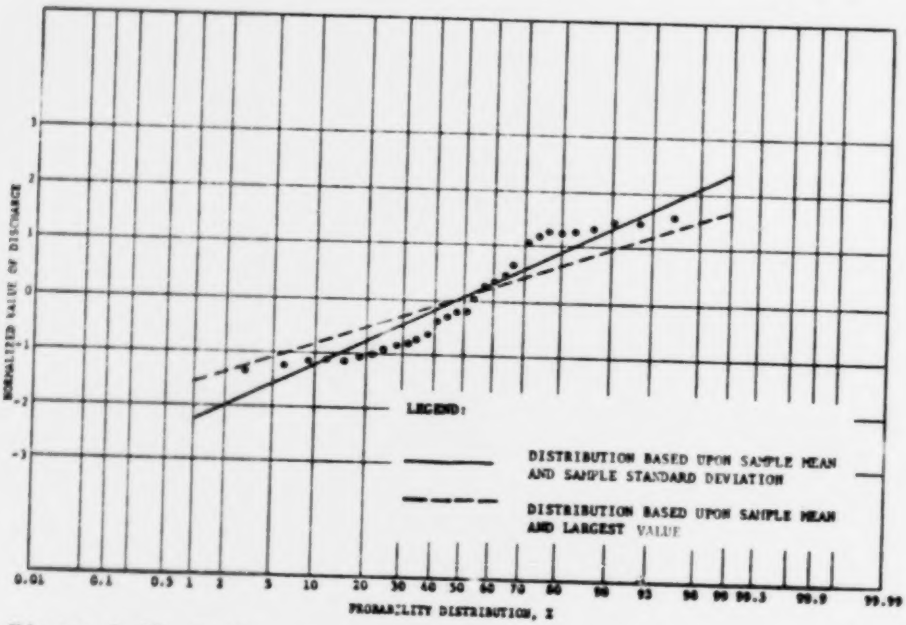

Figure 5.15 Daily samples of BOD loadings from a wet month (normal assumption).

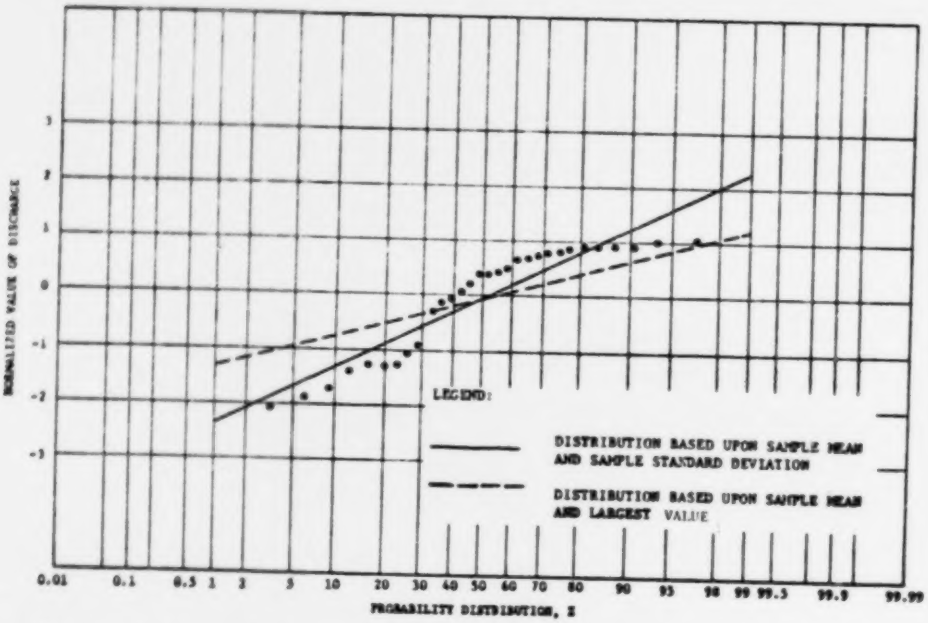

Figure 5.16 Daily samples of BOD loadings from a wet month (lognormal assumption).

assumptions, respectively. While both these assumptions are acceptable, the tail-fit of the distributions that use the maximum likelihood estimate of σ based upon the largest observation (dashed line) is better.

The dry month samples exhibit a more regular behavior than the wet month samples -- the straight line fit is better for the former. Nevertheless the BOD data from both seasons can be accepted as either normal or lognormal. Thus it can be seen that the distributional properties of the BOD samples from a wet month are similar to those from a dry month.

Measurements of suspended solids (dry and wet month) are plotted in Figures 5.17 - 5.18 under the normal and lognormal assumption. A more irregular behavior is observed again during a wet month but the normal or lognormal distribution is still acceptable to describe the variability regardless of season.

A set of 28 coliform measurements (January 1974) are plotted in Figure 5.21 under the lognormal assumption, and again a good fit is observed in the upper tail. This set of data was accepted at 15% significance level as lognormal, but rejected even at $\alpha = 1\%$ as being normal.

The distribution studies performed on the main constituents of a waste treatment plant, (BOD, SS) show that both the normal and the lognormal assumptions can be accepted at a high level of significance. The distribution estimation method based upon monthly mean and monthly maximum developed in Appendix A has been illustrated and shown to give very good fit for the tail of the distribution. A study on coliform data showed that it is best modeled by a lognormal model. From the seasonality study it appears that there can be noticeable changes from season to season of a constituent's statistical description. For the purpose of obtaining the expected damage and the probability of violation, the "adaptive" feature of the Bayesian updating method described in Section V.2 becomes important. This property of the updating procedure will ensure acceptable performance of the priority procedure despite the seasonal variability.

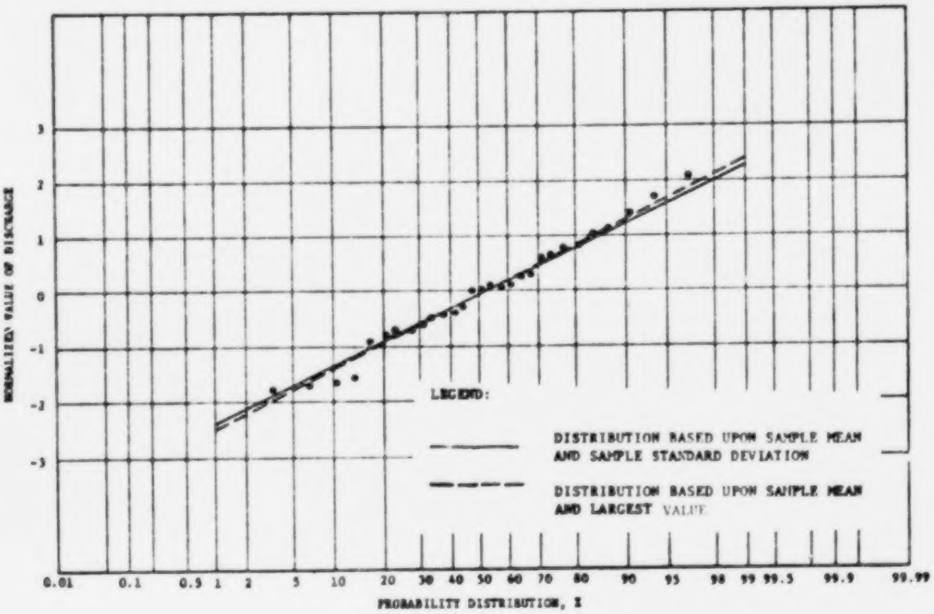

Figure 5.17 Daily samples of suspended solids loadings from a dry month (normal assumption).

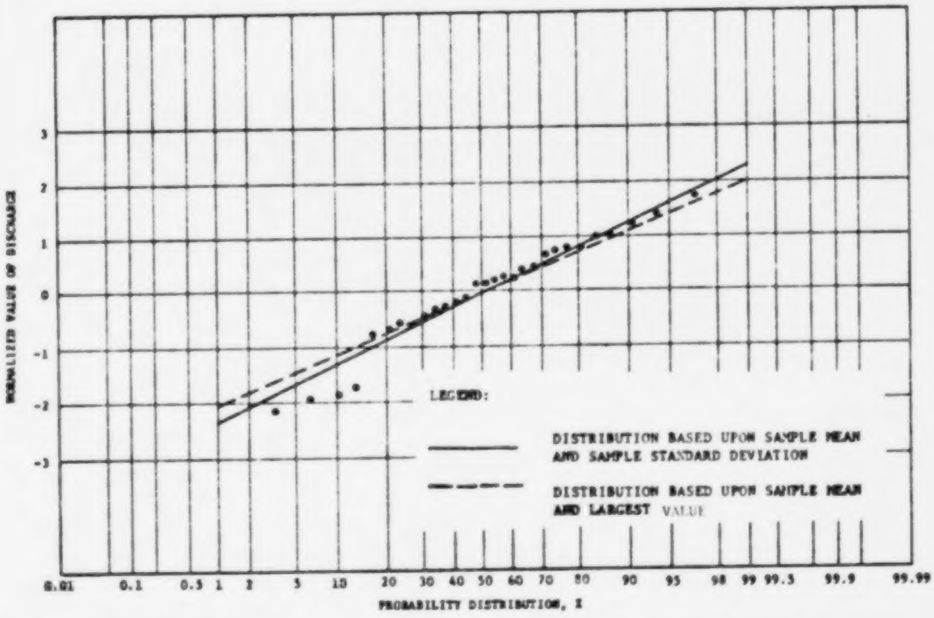

Figure 5.18 Daily samples of suspended solids loadings from a dry month (lognormal assumption).

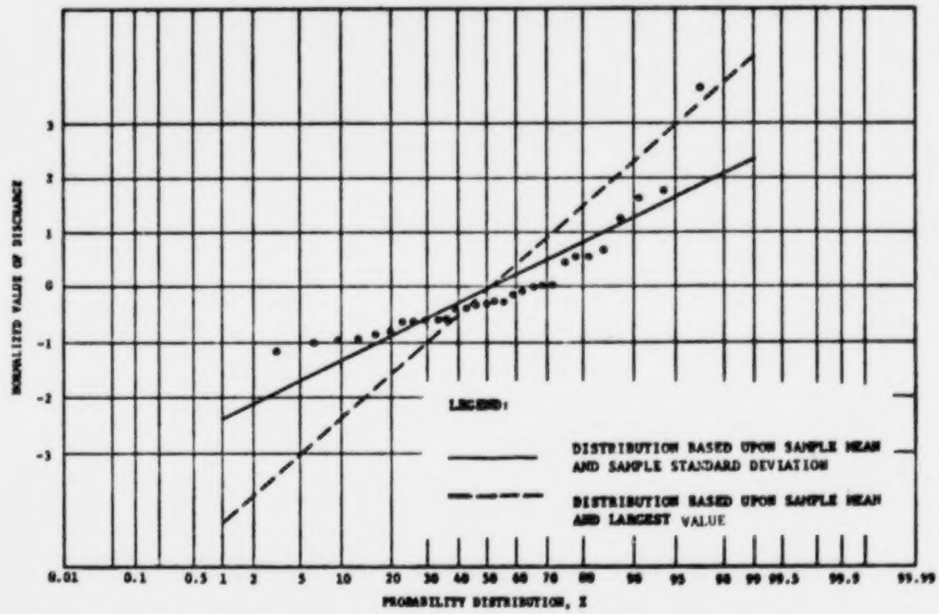

Figure 5.19 Daily samples of suspended solids loadings from a wet month (normal assumption).

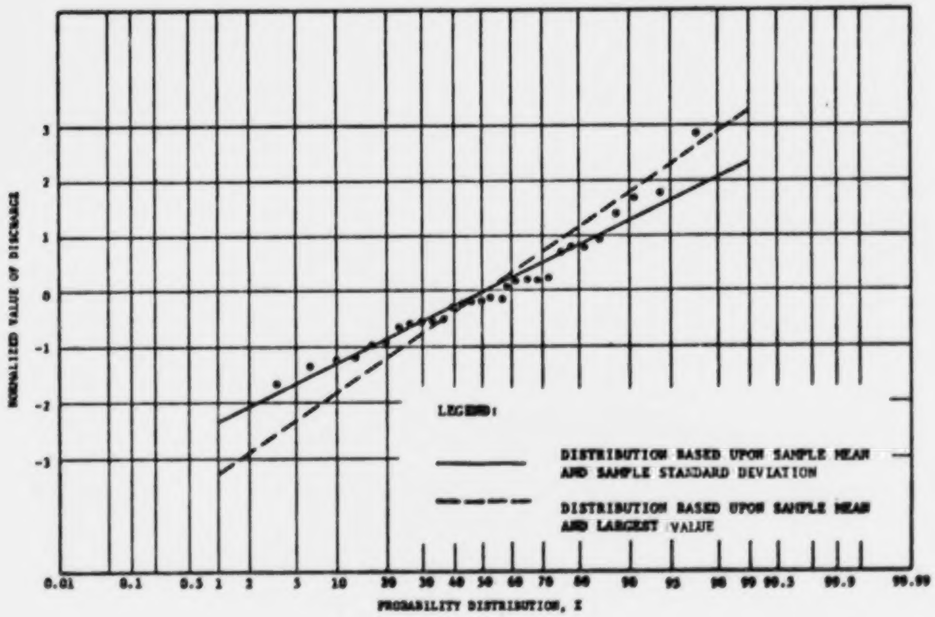

Figure 5.20 Daily samples of suspended solids loadings from a wet month (lognormal assumption).

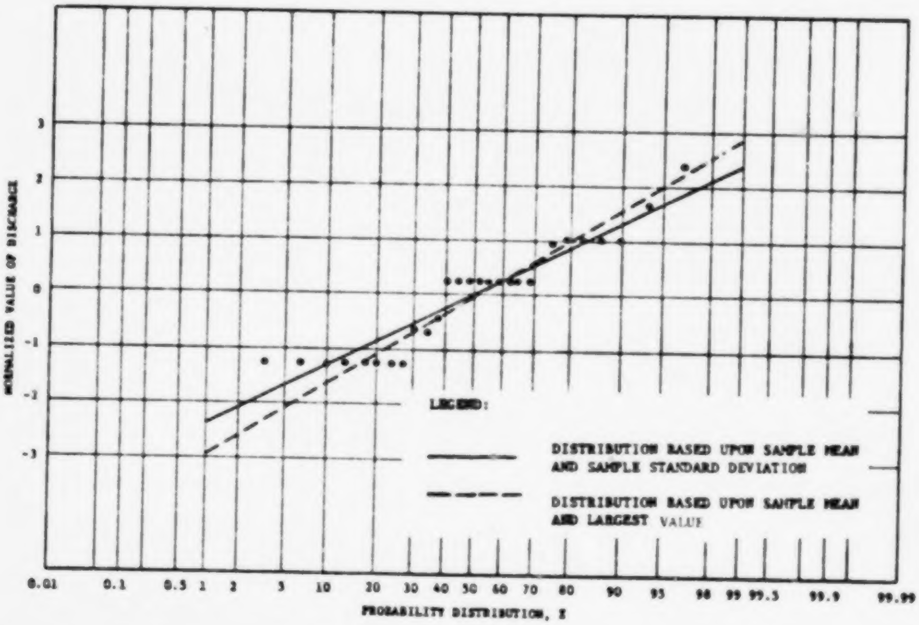

Figure 5.21 Daily samples of coliform loadings (lognormal assumption).

V.2 INITIAL STATISTICAL DESCRIPTION

The monitoring agency will have two types of data available from which it can initially determine the statistical characteristics of the effluent discharges:

- Self-monitoring data
- Compliance data

The self-monitoring reports will typically be sent to the appropriate regulatory agency on a quarterly basis. The reports will, at a minimum, contain the monthly maximum and monthly sample mean of the daily measurements (usually composite) of those constituents for which standards have been set. The report will also state the number of samples which were used to obtain the sample mean and maximum. Compliance data will also be available on the sources the monitoring agency has inspected as part of its compliance monitoring program.

When using the Resource Allocation Program for the first time, it is necessary to obtain an initial statistical description of all the effluent source constituents. This statistical description will be a function of self-monitoring data and compliance monitoring data gathered over many months. The procedure required to obtain the initial statistical description is shown in Figure 5.22. The various components of this procedure will now be discussed.

Aggregate Self-Monitoring Data

The procedure to obtain estimates of the mean and standard deviation from the sample mean and the maximum (given in Appendix A) requires that the number of measurements used to obtain the sample mean and the maximum be greater than three. If the number of measurements is three or less, the data over several months can be aggregated to obtain a

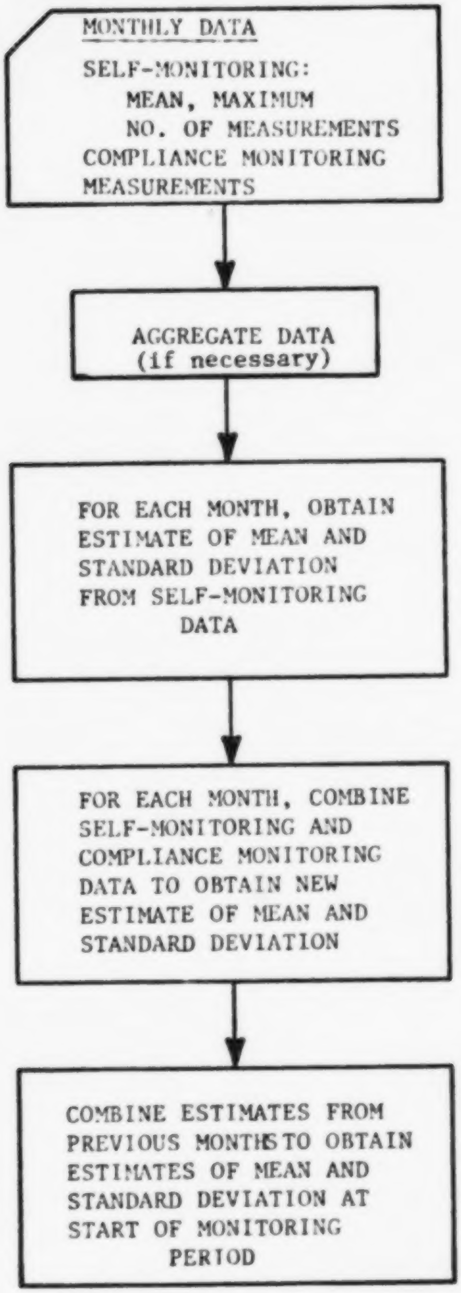
MONTHLY DATA
SELF-MONITORING:
MEAN, MAXIMUM
NO. OF MEASUREMENTS
COMPLIANCE MONITORING
MEASUREMENTS
AGGREGATE DATA
(if necessary)
FOR EACH MONTH, OBTAIN
ESTIMATE OF MEAN AND
STANDARD DEVIATION
FROM SELF-MONITORING
DATA
FOR EACH MONTH, COMBINE
SELF-MONITORING AND
COMPLIANCE MONITORING
DATA TO OBTAIN NEW
ESTIMATE OF MEAN AND
STANDARD DEVIATION
COMBINE ESTIMATES FROM
PREVIOUS MONTHS TO OBTAIN
ESTIMATES OF MEAN AND
STANDARD DEVIATION AT
START OF MONITORING
PERIOD

Figure 5.22 Initial statistical description procedure

sample mean and maximum based on more than three measurements. In this way the estimation procedures of Appendix B, which have been shown in Section V.1 to be applicable to describing the effluent statistics, can still be used. The aggregation procedure is straightforward. Let m_t, y_t and n_t, $t = 1, 2, \ldots, T$, be respectively the sample mean, maximum and number of measurements in month t. Define the index sets $T_1, T_2, \ldots, T_s$ as follows: $T_1 = \{1, 2, \ldots, t_1\}$, $T_2 = \{t_1+1, \ldots, t_2\}, \ldots, T_s = \{t_{s-1}, \ldots, T\}$ so that

$$\hat{n}_i = \left[\sum_{t \epsilon T_i} n_t \right] > 3$$

The data can therefore be treated as just coming from months $t_1, t_2, \ldots,$ T - these shall be called aggregated months. The means of the aggregated months are simply

$$\hat{m}_i = \frac{1}{\hat{n}_i} \sum_{t \epsilon T_i} n_t m_t$$

and the maxima are

$$\hat{y}_i = \max_{t \epsilon T_i} y_t$$

The number of measurements, $\hat{n}_i$, in the aggregated months is greater than three and therefore the standard estimating procedures can be used to obtain estimates of the mean and maximum. Table 5.3 gives an example of the formation of the mean and maxima of the aggregated months.

Obtain Estimates of Mean and Standard Deviation From Monthly Self-Monitoring Data

The estimation procedures to obtain estimates of the mean and standard deviation for normal and lognormal processes are given in Appendix A, and their use was demonstrated in Section V.1.

Table 5.3. EXAMPLE OF AGGREGATION OF DATA

Original data				Aggregated data			
Month t	Number of measurements n_t	Sample mean m_t	Maximum y_t	Month i	Number of measurements $\hat{n}_i$	Sample mean $\hat{m}_i$	Max. $\hat{y}_i$
1	1	4	8				
2	2	5	7				
3	1	4	9	1	4	4.5	9
4	1	4	8				
5	1	4	7				
6	1	3	6				
7	2	4	8	2	5	3.8	8

Combine Self Monitoring and Compliance Monitoring Data

At this point in the procedure, estimates of the mean and standard deviation, based on self-monitoring data, are available for each month or aggregated month. These will be combined with the compliance monitoring data to btain new improved estimates. Since the monitoring agency will be collecting the compliance monitoring data, this data will be more reliable than the self-monitoring data. This should be taken into consideration in the method of combination.

The combination proceeds as follows: let $z_1, z_2, \ldots, z_c$ be c daily composite values obtained in the compliance monitoring program for a month. Let m and v be the estimated mean and variance for that month based on the self-monitoring data. Let n and ν be the parameters which express the confidence in the mean and variance respectively. n and ν are constants representing the equivalent number of measurements used to estimate m and v.* The values of n and ν are set proportionally to the number of measurements, N, used to calculate the monthly mean and maximum, that is

$$n = h_n N \tag{5.1}$$

and

$$\nu = h_\nu (N-1) \tag{5.2}$$

where h_n and h_ν are design parameters.

---

*A discussion of these confidence parameters is given at the end of this section. They are also discussed in Appendix E. For further information see [7].

The compliance data and the monthly estimates are combined sequentially, using the updating formula described in Appendix E. First, the compliance data z_1, are combined with the self-monitoring estimates (m, n, v, ν) using the update formula (E.3), yielding the posterior estimates (m_1, n_1, v_1, ν_1). The second compliance data z_2 are then combined with this estimate to yield a new estimate (m_2, n_2, v_2, ν_2). The process is repeated, until all the compliance data are used, to obtain a final monthly estimate. In order to give the compliance monitoring data more weight (since they will, in general, be more reliable) the values of ν and n used in (E.3a) and (E.3b) should be reduced by some constant, say γ; that is, ν and n should be replaced in the formula (E.3a) and (E.3c) by ν/γ and n/γ where $\gamma>1$ is a design constant.

As an example, consider the case where the estimate of the mean, from self-monitoring data, is $m = 100$ and the estimate of the standard deviation is $\sigma = 25$. The confidence parameters are assumed to be $n = 15$ and $\nu = 10$. Suppose compliance data for the month are also available with values $z_1 = 115$ and $z_2 = 145$. Let γ be equal 2. Using (E.3), z_1 can be combined with the estimates (m, n, v, ν) to yield (recall $n' = 1$ and $\nu' = 0$)

$$m_1 = \frac{(n/\gamma)m + z_1}{(n/\gamma) + 1} = 101.8$$

$$n_1 = n + 1 = 16$$

$$v_1 = \frac{[(\nu/\gamma)v + (n/\gamma)m^2] + z_1^2 - ((n/\gamma) + 1)m_1^2}{(\nu/\gamma) + 1} = 543.7$$

$$\nu_1 = \nu + 1 = 11$$

The new estimate of the standard deviation is $\sigma_1 = \sqrt{v_1} = 23.3$. The process is then repeated with (m_1, n_1, v_1, ν_1) replacing (m, n, v, ν) and z_2 replacing z_1 to yield

$$m_2 = 106.6$$

$$n_2 = 17$$

$$v_2 = 715.27$$

$$\nu_2 = 12$$

The new estimate of the standard deviation is $\sigma_2 = 26.7$. Figure 5.23 shows how the assumed density function would change for this example.

Combine Estimates from Several Months

The final step in obtaining an initial statistical description is to combine the estimates from several months to obtain an estimate of the mean and standard deviation at the start of the monitoring period. The estimates are combined by sequentially using the Bayesian update formula given in Appendix E. If the mean m_t and the variance v_t, along with the confidence parameters n_t and ν_t, are available for months $t = 1, 2, \ldots, T$, the final estimates would be obtained by first combining (m_1, n_1, v_1, ν_1) and (m_2, n_2, v_2, ν_2) using (E.3) yielding $(m_2', n_2', v_2', \nu_2')$. Then $(m_2', n_2', v_2', \nu_2')$ would be combined with (m_3, n_3, v_3, ν_3) to yield $(m_3', n_3', v_3', \nu_3')$. This process would be repeated until the estimate $(m_T', n_T', v_T', \nu_3')$ is obtained, which is the estimate to use in the priority setting procedure.

Confidence Parameters

In order to use the Bayesian update formula, it is necessary to specify the confidence parameters n and ν. These parameters describe one's confidence in the estimates of the mean and standard deviation. For the case when the statistics of the process are normal or lognormal and stationary, and the estimates used are the sample mean and sample

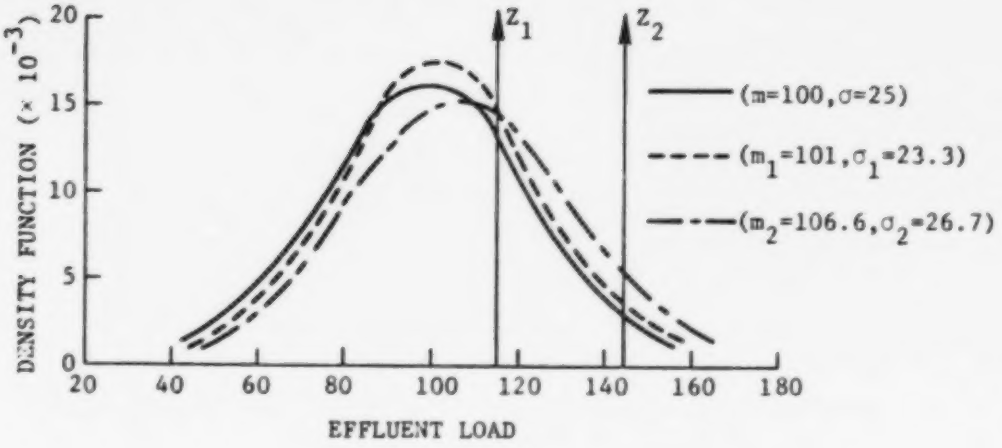

Figure 5.23 Example of inclusion of compliance monitoring information

standard deviation of N data points, n would be set equal to N and ν equal to N-1. In the present case, the statistics are not exactly normal or lognormal, the process is not, in general, stationary, and the estimate of the standard deviation is not the sample standard deviation. For these reasons the specification of n and ν must be based on the following subjective factors:

(1) In order to take trends into account and to discount past information, the value of n and ν in the updating formula must not be allowed to get too large. This can be accomplished by requiring $n \leq k_n n'$ and $\nu \leq k_\nu \nu'$ in (E.3) where k_n and k_ν are given constants. Therefore, if the update formula results in $n > k_n n'$ or $\nu > k_\nu \nu'$ then set $n = k_n n'$ and $\nu = k_\nu \nu'$.

(2) For the normal case, the estimate of the mean is the sample mean and so a reasonable value for h_n in (5.1) is 1 for this case. The estimate of the mean for the lognormal case should also be very efficient, and so again a value of $h_n = 1$ is suggested.

(3) The efficiency of the estimates of the standard deviation obtained from the sample mean and maximum is unknown. They should, however, be on the same order as the estimates of the standard deviation that can be obtained from the range (the range is the difference between the largest and smallest values from a sample). It is shown in Appendix A that the relating efficiency of this estimate varied from 1.0 when there were two samples to 0.49 when there were 50 samples (see Table A.3.3). It is suggested that h_ν be set equal to the value of relative efficiency indicated in Table A.3.3.

V.3 UPDATE OF STATISTICS

In the previous section, a procedure was given to obtain the statistical characteristics of the effluent sources at the commencement of the use of the Resource Allocation Program. The Resource Allocation Program will be used on a periodic basis to obtain the sampling frequencies for each following monitoring period. At the same time the monitoring agency will continue to receive self-monitoring and compliance data. The purpose of this section is to describe how this data should be used to obtain an updated statistical description.

The update procedure is identical to the procedure described in Section V.2, with the small exception that the old statistical characterization is used as a starting point in the procedure. To be precise, the statistical update procedure follows the Initial Statistical Description procedure (see Figure 5.22) in that first the new monthly data are aggregated, if necessary, to obtain sample sizes greater than 3; estimates of the mean and standard deviation based on the self-monitoring data are then obtained. The Bayesian update formulas (Appendix E) are then used to combine the compliance monitoring data and the monthly statistics based on self-monitoring. At this point the original statistical description of the effluent and the new monthly statistical description based on the new data are available. These are combined sequentially, starting with the original statistics, using the Bayesian update formula, thereby obtaining an updated statistical description.

SECTION VI

"COST" OF UNDETECTED VIOLATIONS

The purpose of compliance monitoring is to ascertain whether pollutant loads in permitted discharges are in compliance with the limits specified in the permits. In determining how often to sample a particular effluent source in a monitoring period, several factors should be taken into account, including

- How often a violation is expected
- The expected magnitude of the violation
- The toxicity of the pollutants
- The assimilative capacity of the receiving waters at the discharge point.

A performance index called the "cost" of undetected violations, which depends on these factors, is derived in this section. The decision variable is the number of times each source is to be monitored in a monitoring period (i.e. the sampling frequencies). The "cost" is defined as the expected value of the damage caused by the pollutants of sources not found in violation of their standards. "Costs" are only associated with undetected violations, because if a source is monitored and found in violation of a standard, then the monitoring agency has done its job and no "costs" should therefore be associated with that visit.

The performance index depends on (i) the statistical descriptions of the pollutant loadings, (ii) the damage functions, (iii) the relationship between the pollutant loading and the concentration of the corresponding water quality indicator in the stream, and (iv) the effluent standards. The "costs" discussed here are environmental costs and not monetary costs. The value of the performance index will not correspond to a dollar amount. This is the reason that the word "cost" is being set off in quotation marks.

The "cost" of undetected violations for a given source can be written as the product of two terms. The first term is the expected damage caused by the pollutants of the source. This damage is defined as the environmental damage to the receiving waters caused by the effluent source's constituents. Since the environmental damage due to a specific concentration of pollutant in the stream varies greatly with the nature of the pollutant, it is necessary to define a damage function. This damage function assigns a value to a given concentration of pollutant in the receiving waters. In this way, for example, a small concentration of mercury and a relatively large concentration of suspended solids can give the same value of damage. The second term in the "cost" of undetected violations is the probability that no violation is detected at the source. This term reflects the fact that as a source is sampled with increasing frequency, the probability that a violation will go undetected will decrease. To recapitulate, the "cost" of undetected violations from a source is the product of two terms:

- The expected damage from the source
- The probability that the source will not be in violation

The remainder of this section will (i) investigate the effect on the receiving waters of the effluent load, (ii) define damage functions for various pollutants, and (iii) derive in detail the "cost" of undetected violations.

VI.1 EFFECT ON AMBIENT QUALITY DUE TO EFFLUENT LOADS

Receiving water damages are assumed to be a direct function of the constituent concentrations. The method of estimating receiving water concentrations resulting from various types of effluent discharges is described below.

In the computation of receiving water concentrations, "far-field" spatial and temporal scales are used [8]. In practice, the far-field concept restricts the spatial scales of interest. Streams and vertically well mixed estuaries and reservoirs can be treated as one dimensional flows with only longitudinal variations in concentration. Effluent discharges located in very close proximity may be "clustered" and treated as discharges entering a single point.

The far-field concept also permits the use of net flows and velocities in estuaries. In the short term, estuarine flows primarily fluctuate in a cyclic manner related to tidal heights, but the long term trend is for the estuarine waters to flow toward the sea at a magnitude approximately equal to the river flow into the estuary. Using this concept, the advective nature of estuaries is related only to the net seaward flow, which can be estimated using the sum of incoming river flows.

The far-field approach enables usage of simple water quality modeling techniques presented in [9]. Models which describe the three dimensional aspects of mixing in the near field with temporal variations are not needed. Since Water Quality Standards are given for areas outside of some mixing zone, the use of the far-field concept fits well with the law, permits the development of tractible procedures for deriving concentration, and enables subsequent damage function predictions.

Constituent Selection

Table 6.1 lists the water constituents which have been considered in this study. The different types of constituent behavior are discussed in the following subsection. These constituents were selected on the basis of their presence in the existing Federal Effluent Guidelines [10-26], and their probable presence in various industrial and domestic effluent discharges. Except for dissolved oxygen, receiving water concentrations of each of the listed constituents are directly proportional to the magnitudes of their respective effluent loadings. Adverse effects of effluents upon dissolved oxygen are indirectly caused by loadings of biochemical oxygen demand (BOD) and chemical oxygen demand (COD). The impact upon dissolved oxygen due to a BOD or COD load can be expressed in terms of a simple transfer coefficient multiplied by the receiving water concentration of BOD or COD caused by the load. Therefore, the damages due to loadings of BOD and COD, as well as all the other pertinent constituents, can be found directly through their predicted concentrations along the stream.

Stream Impact Characterization

For purposes of this study, rivers, estuaries and reservoirs are treated as one-dimensional systems with only net downstream velocities. In this context, all of these receiving waters are treated as streams. The mathematical models used to describe the impact of the waste constituents in streams are classified as either conservative, or non-conservative non-coupled. The analysis of the coupled constituent, dissolved oxygen, is performed through modeling of the non-conservative, non-coupled constituents, BOD and COD.

Conservative constituents are those which do not decay in the stream with time. The constituent concentration is reduced only by dilution. Figure 6.1 illustrates the spatial characteristics of a conservative constituent with a single waste source entering the stream. The only factors affecting the stream concentration of the j^{th} conservative

Table 6.1. BEHAVIOR OF WATER CONSTITUENTS

Constituent Name	Behavior *	Constituent Name	Behavior
Aluminum (total)	C	Lead (total)	NN
Ammonia	NN	Manganese (total)	NN
Dissolved Oxygen	NC	Mercury	NN
Total Inorganic Carbon	C	Nickel (total)	NN
Chloride	C	Nitrogen	NN
Chloroform Extract (measure of taste & odor potential)	NN	Oil-Grease	NN
		pH-MIN	NN
Chromium (total)	NN	pH-MAX	NN
Coliforms-Total	NN	Phenol	NN
Coliforms-Fecal	NN	Phosphorus	NN
Copper (total)	NN	Solids-Dissolved	C
Cyanide	NN	Solids-Suspended	NN
Fluoride (total)	C	Temp. Diff.	NN
Iron (total)	NN	Tin (total)	NN
		Zinc (total)	NN

*C - conservative

NN - non-conservative, non-coupled

NC - non-conservative coupled

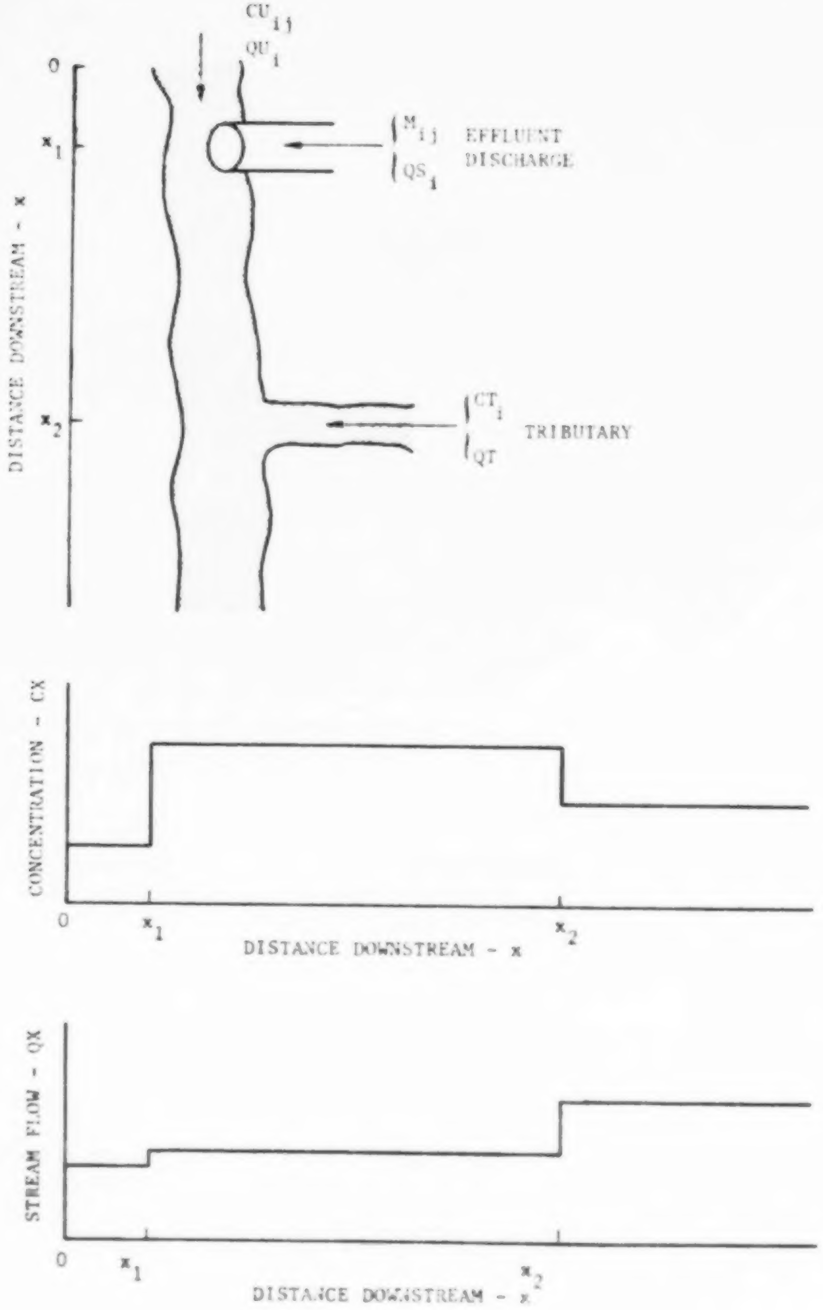
CU_ij
QU_i
0
x_1
x_2
DISTANCE DOWNSTREAM - x
M_ij
QS_i
EFFLUENT DISCHARGE
CT_i
QT
TRIBUTARY
CONCENTRATION - CX
0
x_1
x_2
DISTANCE DOWNSTREAM - x
STREAM FLOW - QX
0
x_1
x_2
DISTANCE DOWNSTREAM - x

Figure 6.1 Stream characterization of conservative constituents [B].

constituent due to the i^{th} effluent source are the upstream flow in the stream QU_i, the net[*] effluent mass load M_{ij}, mean effluent flow rate QS_i, and the upstream concentration CU_{ij}. The flow in the stream below discharge i may be written as

$$QX_i = QU_i + QS_i \tag{6.1}$$

The concentration in the stream immediately downstream from the i^{th} source is[†]

$$CO_{ij} = \frac{M_{ij} + CU_{ij}\ QU_i}{QX_i} \tag{6.2}$$

For conservative constituents this stream concentration persists downstream until new effluent or water sources either dilute or add to it.

Non-conservative, non-coupled mathematical models are used to characterize water quality constituents whose concentrations vary with both time and dilution. For these constituents first-order kinetics are assumed and a decay rate coefficient assigned for each parameter. Figure 6.2 illustrates the case of a non-conservative, non-coupled constituent. It assumes that the physical characteristics of the stream are uniform over the distance shown so that the decay coefficient (k) and the stream velocity (v) are constant. The equation describing the steady-state spatial characteristics of a non-conservative, non-coupled constituent below a single source (downstream of x_1 in Figure 6.1) is

$$CX_{ij} = \left(\frac{M_{ij} + CU_{ij}\ QU_{ij}}{QX_i}\right) e^{-K(x-x_1)/v} \tag{6.3}$$

---

[*] The word "net" is used to account for industries that withdraw polluted water from a stream and then discharge it in somewhat changed form. Those industries should not be penalized for their polluted intake water.

[†] Care must be taken in maintaining proper units in this equation. In this regard the following suggestions are made. For temperature the constitutent mass (M_{ij}) should be expressed in terms of heat (temp x flow), for pH the mass term should be expressed as the net effluent ion concentration multiplied by its flow (see Appendix C for more details on pH), and for coliforms the net effluent coliform concentration (MPN/100ml) should be multiplied by its flow.

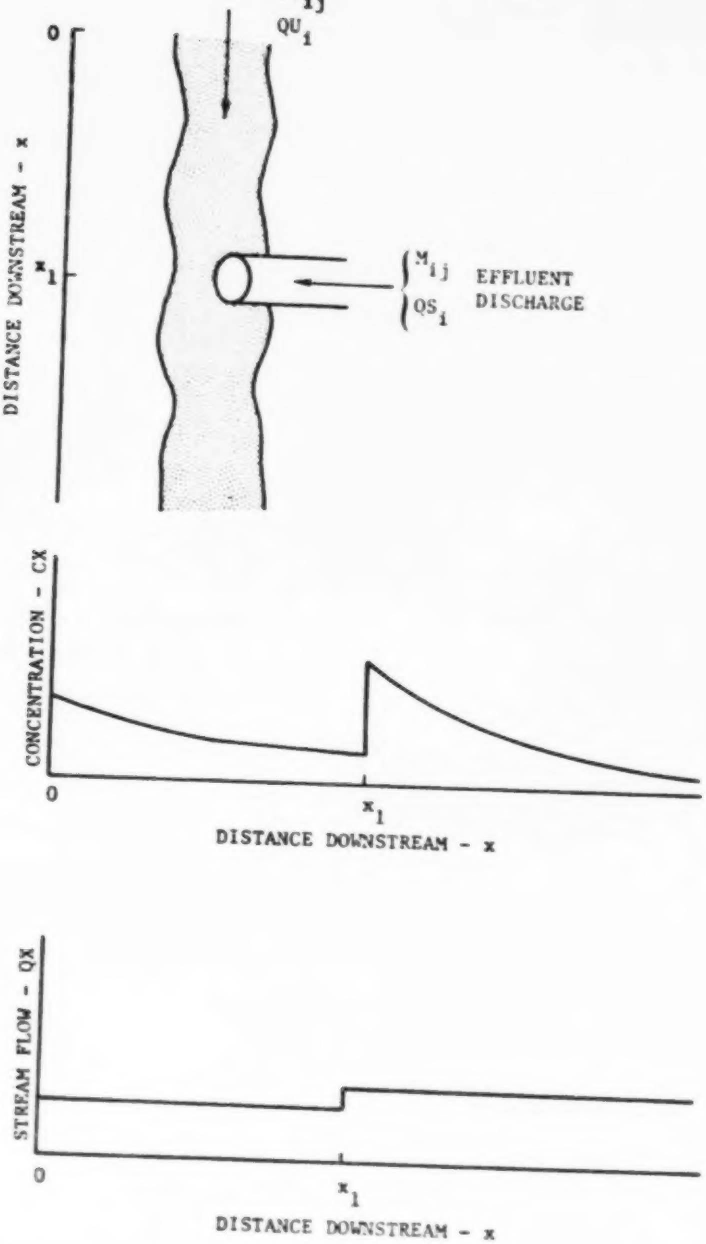
CU_ij
QU_i
0
x_1
DISTANCE DOWNSTREAM - x
M_ij
QS_i
EFFLUENT
DISCHARGE
CONCENTRATION - CX
0
x_1
DISTANCE DOWNSTREAM - x
STREAM FLOW - QX
0
x_1
DISTANCE DOWNSTREAM - x

Figure 6.2 Stream characterization of non-conservative, non-coupled constituents [B].

An effluent damage is considered to be a function of its maximum impact at any point of the stream. From Figures 6.1 and 6.2 it can be seen that the maximum concentration impact due to discharge of a non-coupled constituent occurs at the discharge point. Therefore, the damage functions can be related to the initial diluted stream concentration of constituents:

$$\text{Damage} \propto CO_{ij} = \frac{M_{ij} + CU_{ij}\ QU_{ij}}{QU_i + QS_i} \qquad (6.4)$$

The input mean stream flows and discharge flows are usually available from historical data. The varying mass loads are input in statistical form as shown in Section V. A discussion concerning the value of upstream concentration to use in (6.4) is given in Section VI.2

Dissolved Oxygen Damages

The presence of BOD or COD in receiving waters induces a two step reaction in which BOD (or COD) decays, in the process depleting the available dissolved oxygen, and the oxygen replenishes itself through natural air-water interaction. The difference between the saturated level of dissolved oxygen (DOSAT) and the actual level is called the dissolved oxygen deficit (D). The maximum dissolved oxygen deficit due to BOD load from effluent i ($D_{i,BOD}$) can be approximated in terms of a transfer coefficient (K_{BOD-DO}) multiplied by the initial stream BOD concentration [9], i.e.,

$$D_{i,BOD} = (K_{BOD-DO})(CO_{i,BOD}) = K_{BOD-DO}\left[\frac{M_{i,BOD} + CU_{i,BOD}QU_i}{QX_i}\right] \qquad (6.5)$$

Similarly for COD

$$D_{i,COD} = (K_{COD-DO})(CO_{i,COD}) = K_{COD-DO}\left[\frac{M_{i,COD} + CU_{i,COD}QU_i}{QX_i}\right] \qquad (6.6)$$

A simple method for obtaining the transfer coefficients, K_{BOD-DO} and K_{COD-DO}, is presented in Appendix F.

The damage due to a BOD or COD load is related to the minimum expected level of dissolved oxygen due to the load. This minimum DO level is computed as

$$DOMIN_{i,BOD} = \begin{cases} CO_{i,DO} - D_{i,BOD}, & \text{if } CO_{i,DO} \geq D_{i,BOD} \\ 0 & \text{, otherwise} \end{cases} \qquad (6.7)$$

for BOD and

$$DOMIN_{i,COD} = \begin{cases} CO_{i,DO} - D_{i,COD}, & \text{if } CO_{i,DO} > D_{i,COD} \\ 0 & \text{, otherwise} \end{cases} \qquad (6.8)$$

for COD. $CO_{i,DO}$, the dissolved oxygen concentration at the point of discharge, is

$$CO_{i,DO} = \frac{CS_{i,DO}\ QS_i + CU_{i,DO}\ QU_i}{QX_i} \qquad (6.9)$$

where $CS_{i,DO}$ and $CU_{i,DO}$ are respectively, the concentration of DO in the source effluent and in the receiving waters upstream from the source. (6.7) and (6.8) are conservative (i.e. low) estimates of DOMIN. The transfer coefficient, K_{BOD-DO} in (6.5) is derived assuming the DO is at saturation at the point of BOD discharge. If DO is not in saturation, then the decrease in DO will be somewhat less then the value given in (6.5)-(6.6).

VI.2 DAMAGE FUNCTIONS

The damage function relates environmental damage to a given concentration of various pollutants in a stream. There have been two basic approaches to characterizing damage functions: (1) a subjective definition [27], [28], [29] where the shape of damage function curve was related to, for example, the effect on fish, fitness to drink, fitness for recreation, etc.; or (2) an economic definition [30], [31] where the damage is related, for example, to the cost of returning the water to a point where pollutant levels are below some standard. Both of these types of damage functions have drawbacks. The "subjective" damage function is hard to quantify into a single function. Most bodies of water have varied uses and a particular pollutant will affect the various uses to different degrees. Even if only a single water use is affected, there is disagreement for most pollutants as to what level of pollutant causes the water to be of acceptable quality or to be polluted. The "economic" damage function, on the other hand, can yield costs which are related to attributes other than environmental damage. If, for example, the damage is related to the cost of restoring the quality of the stream then a pollutant which is more difficult to remove or dilute but does little environmental harm will cause more "damage" than one which is easier to remove but causes greater environmental damage. The economic approach also has the problem that it may be difficult to obtain the data needed to define the damage function.

The "subjective" damage function has been chosen for this study. It has the advantage of reflecting environmental damage without bringing into consideration unimportant factors such as cost of water for dilution. Also, for the purposes of the priority procedure, the damage functions are only used so that concentrations of various pollutants can be compared with respect to environmental damage. The actual values given to the damage functions and the decision as to when a concentration of a pollutant causes the waters to be "polluted" are not that important as long as the rules for defining the damage functions are consistent.

The damage function is defined as a piecewise linear function where a numerical value is given to each "Level of Damage" - the values 0, 2, 4, 6, 8 and 10 correspond to "none", "excellent", "acceptable", "slightly polluted", "polluted", and "heavily polluted", respectively. This type of damage function closely follows the approaches used by Prati [27], Horten [28], and McClelland [29]. Using [28] - [29] and [32] - [34], damage functions were defined for 26 water quality indicators. These damage functions are given in Table 6.2. Figure 6.3 gives an example, in graphical form, of a damage function; the indicator considered is suspended solids.

Table 6.2 DAMAGE FUNCTIONS

Constituent name	Units	Level of damage						Reference*
		None 0	Excellent 2	Acceptable 4	Slightly polluted 6	Polluted 8	Heavily polluted 10	
Aluminum	mg/l	0	0.01	0.05	0.10	.50	1.00	34
Ammonia	mg/l	0	0.1	0.3	0.9	2.7	3.0	27
Dissolved oxygen	mg/l	>9	8.0	6.8	4.5	1.8	0.9	32
Inorganic carbon	mg/l	<50	70	90	110	130	150	32
Chloride	mg/l	0	25	175	200	240	250	28
Chloroform extract	mg/l	0	0.04	0.15	0.25	0.35	0.40	28
Chromium	mg/l	0	0.02	0.05	1.0	10.0	50.0	33,34
Coliforms-total	MPN/100ml	0	100	2000	7500	15,000	150,000	28,33
Coliforms-fecal	MPN/100ml	0	20	200	800	3,000	50,000	29,32
Copper	mg/l	0	0.02	0.10	1.00	5.00	10.00	33,34
Cyanide	mg/l	0	0.01	0.02	0.05	0.10	0.50	33,34
Fluoride	mg/l	<0.7	0.8	0.9	1.2	3.0	8.0	34
Iron	mg/l	0	0.1	0.3	0.9	2.7	3.0	27
Lead	µg/l	0	5	50	100	250	350	33,34
Manganese	mg/l	0	0.05	0.17	0.50	1.00	1.50	27
Mercury	µg/l	0	1	5	10	20	50	34
Nickel	mg/l	0	0.01	1.0	3.0	9.0	20.0	34
Inorganic nitrogen	mg/l	<0.6	0.9	3.0	4.5	7.0	10.0	32
Oil-grease	mg/l	0	0.01	0.10	5	30	50	34
pH-MIN		7	6.5	6.0	5.0	4.0	3.9	27
pH-MAX		7	8.0	8.4	9.0	10.0	10.1	27
Phenol	µg/l	0	0.5	1.0	20	100	200	33,34
Phosphates	mg/l	0	0.1	0.2	0.5	1.6	10	29
Solids-dissolved	mg/l	<100	200	500	1000	1500	2300	32
Solids-suspended	mg/l	0	20	40	100	280	300	27
Temp. diff.	°C	0	1.0	2.5	3.0	4.0	10.0	29
Tin	mg/l	0	10	40	100	300	1000	33,34
Zinc	mg/l	0	0.1	1	5	15	40	34

*The references shown are those used to develop the damage function for each constituent.

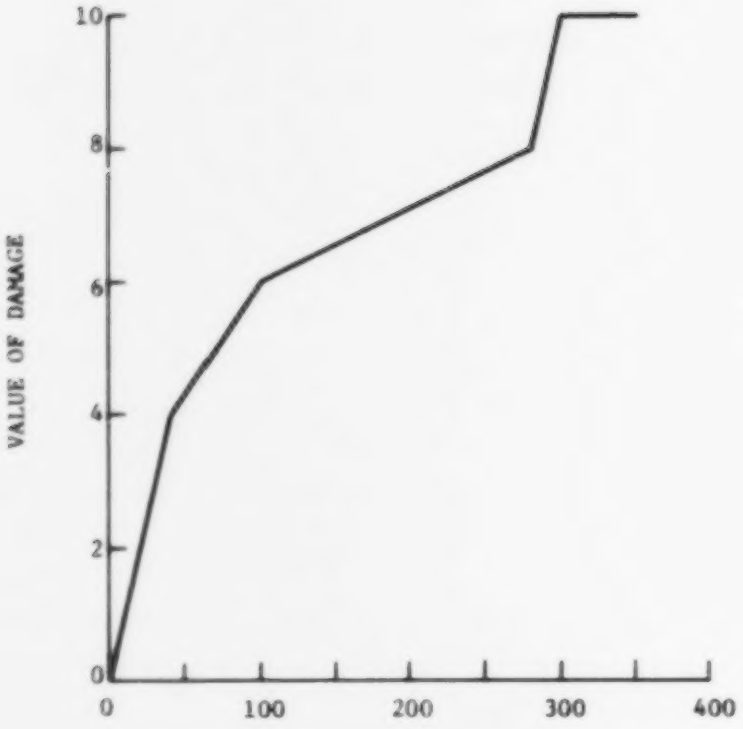

Figure 6.3 **Example damage function**

It should be noted that the damage functions given in Table 6.2 exhibit just one of many possible choices for damage functions definitions. A monitoring agency should feel free to modify or change the damage functions as it sees fit, especially as more detailed and extensive reports relating damages to water quality become available. Also, the damage functions could be completely eliminated, if desired, by setting them equal to one for all values of the water quality indicators. This would eliminate damage in the resource allocation criterion, the choice of sampling frequency would then just depend on the probability of violation.

VI.3 FORMULATION OF "COST" OF UNDETECTED VIOLATIONS

The "cost" of undetected violations will now be derived. For the present it will be assumed that only one set of effluent standards is given for each source. This corresponds to the case in which there is a single outfall or the permits are written for the combined discharge from several outfalls. The case where there are several sets of standards for several outfalls will be treated at the end of this section.

Let M_{ij} be the mass loading of the j^{th} constituent from the i^{th} source. M_{ij} is modeled as either a normal or lognormal random variable with known mean and standard deviation. Let ϕ_{ij} be the density function of M_{ij}. The concentration of the corresponding stream parameter below the source is

$$CO_{ij} = a_{ij} M_{ij} + b_{ij} \qquad (6.10)$$

where a_{ij} and b_{ij} depend on the effluent and upstream flow, the assumed upstream concentration, and, where needed, other stream parameters* (see Section VI.1 and Appendix C). All the quantities needed to calculate a_{ij} and b_{ij} in (6.10) are readily available to the monitoring agency except for the concentration of the water quality indicators upstream from the source (denoted CU_{ij}). Even if knowledge of CU_{ij} were available, it does not make sense to use an actual value of upstream concentration in the priority procedure. This can be seen by considering the case of two similar plants, one slightly upstream from the other on the same river. If the actual upstream concentration were used, the plant further downstream would always be causing more damage (as measured by the downstream concentration of pollutants); this clearly is not equitable. If only the change in damage were considered, then the plant upstream would typically be penalized, since the change in damage for a given increase in pollutant concentration typically gets smaller as the concentration of pollutant increases. In other words, most of the damage functions are concave in shape. Instead of using an actual value of upstream concentration, it is suggested that the upstream concentration of all the pollutants in the basin be set so as to cause the same level of damage immediately upstream from each source. Clearly, the concentrations could be set to cause no damage upstream; this corresponds to setting the upstream concentration to zero for most water quality indicators. Nonzero initial damages might be desired in order to eliminate the sensitivity of the priority procedure to the damage function definitions for small values of damage. This method of setting CU_{ij} is equitable and is consistent with the priority procedure.

---

*If the effluent standard is written in terms of the concentration of pollutant, the formula for CO_{ij} is in the same form as (6.10) with M_{ij} replaced by $CS_{ij}\,QS_{ij}$ where CS_{ij} is the concentration of pollutant j in the effluent and QS_{ij} is the source flow.

The damage due to the j^{th} constituent from the i^{th} source is $D_j(CO_{ij})$, where D_j is the damage function for the j^{th} constituent. Note that $D_j(CO_{ij})$ is a random variable with statistics depending on the statistics of M_{ij}. The expected damage due to the j^{th} constituent of the i^{th} source is then

$$D_{ij} = E\{D_j(CO_{ij})\} \tag{6.11}$$

or (using (6.10))

$$D_{ij} = \int D_j({}_{ij}M + b_{ij})\ \phi_{ij}(M)dM \tag{6.12}$$

The calculation of D_{ij} is carried out in detail in Appendix C. The expected damage from all the constituents of the i^{th} source (if unmonitored) is

$$c_i = \max_j D_{ij} \tag{6.13}$$

since the pollutant that causes the most damage is the one that limits the water quality. Note that (6.13) assumes that there is no synergistic or antagonistic interaction among the pollutants. This assumption is valid in general. For the purposes of this report, the extra complexity needed if this assumption were to be dropped is not warranted. The total damage that can be expected from all the sources, n_s, in the region is then

$$\sum_{i=1}^{n_s} c_i \tag{6.14}$$

Taking the damage as additive corresponds to assuming noninteraction between the various sources.

The derivation leading to (6.14) did not take into account the fact that we are only interested in undetected violations. The effect of the monitoring on the "cost" will be accounted for as follows: it is assumed that if, during the period of consideration, one of the constituents of a given source is found to exceed its standard, say τ_{ij}, the purpose of the monitoring has been achieved and the "cost" due to that source will be considered zero. Consequently, a violation is declared if at least one constituent is found to exceed its specified standard. Let p_{ij} be the probability that no violation will be observed in one sample of M_{ij}, i.e.,

$$p_{ij} = \int_0^{\tau_{ij}} \phi_{ij}(M)dM \, . \tag{6.15}$$

In view of the above discussion, the expected "cost" of undetected violations is obtained as follows. Assume that the i^{th} effluent is sampled

s_i times during the period consisting of N intervals (e.g., days). Denote by V_i the event that a violation is observed when sampling the effluent. Then, the total "cost" incurred due to the i^{th} effluent when it is sampled s_i times is, using the total probability law, the expected damage given that the standard violation was not detected times the probability that the violation was not observed plus the expected damage given that a violation was detected times the probability that a violation will be observed. Mathematically this can be written

$$C_i(s_i) = \frac{1}{N} E\left\{\sum_{k=1}^{N} d_i(k) \middle| \bar{V}_i\right\} P\left\{\bar{V}_i \middle| s_i\right\} + \frac{1}{N} E\left\{\sum_{k=1}^{N} d_i(k) \middle| V_i\right\} P\left\{V_i \middle| s_i\right\} \tag{6.16}$$

where $d_i(k)$ is the damage incurred due to the i^{th} source during the k^{th} interval and where $\bar{V}_i$ denotes the event that no violation is observed when sampling the source. The division by N, the number of intervals in the monitoring period, is just a normalization factor so that the damage is averaged over the monitoring period. If a violation is detected, the cost is zero, i.e., the second term on the right hand side above is zero. This follows from the fact that we are dealing with the cost of undetected violations and a detected violation should not enter in this cost. Therefore (6.16) becomes

$$C_i(s_i) = \frac{1}{N} E\left\{\sum_{k=1}^{N} d_i(k) \middle| \bar{V}_i\right\} P\left\{\bar{V}_i \middle| s_i\right\} \tag{6.17}$$

Dropping the time dependence (variable k), one has

$$C_i(s_i) = c_i \; P(\bar{V}_i | s_i) \tag{6.18}$$

where c_i, the expected damage due to source i, is given in (6.13). The probability that no violation is observed when the source is sampled s_i times is (assuming independence between the concentrations at various sampling times)

$$P(\bar{V}_i | s_i) = p_i^{s_i} \tag{6.19}$$

Substituting this into (6.18) one obtains

$$C_i(s_i) = c_i \, p_i^{s_i} \tag{6.20}$$

The calculation of p_i, the probability that source i will not be in violation in one sampling, depends on the probability each constituent of source i will not be in volation, p_{ij}, and on the statistical dependence between the various constituents. The probability that no violation is observed in one sampling of source i, assuming independence between the various constituents, is

$$p_i = \prod_j p_{ij} \tag{6.21}$$

If the constituents are completely correlated, then

$$p_i = \min_j p_{ij} \tag{6.22}$$

Since data are not readily available to ascertain the exact correlation between the various constituents of a source, either complete dependence or independence must be assumed.

The "cost" of undetected violation is, therefore,

$$C = \sum_{i=1}^{n_s} C_i(s_i)$$

$$= \sum_{i=1}^{n_s} c_i p_i^{s_i} \tag{6.23}$$

where, for the i^{th} source, s_i is the number of times the source is monitored, c_i is the expected damage, and p_i is the probability the source will not be found in violation if it is monitored once.

It remains to consider the case where there are several outfalls, each with its own set of standards. The outfalls can flow into one stream or into different streams. First consider the case where the outfalls flow into a single stream. The damage depends on the total mass load of pollutants. Assuming the outfalls lie close to each other, the expected damage can then be calculated in the usual way, using a combined mass load and flow rate. This is discussed further in Appendix C. Let $D_{ij\ell}$ be the expected damage due to the j^{th} constituent from source i into stream ℓ. The expected damage due to the i^{th} source from all the constituents into all streams is then (analogous to (6.13))

$$c_i = \max_{j,\ell} D_{ij\ell} \qquad (6.24)$$

The calculation of the probability of no violation is straightforward since, assuming that the effluents from the various outfalls are independent, the probability of no violation from all the outfalls is the product of the probability of no violation in each of the outfalls. To be precise, let

p_{ijk} = probability of no violation due to pollutant j, outfall k, source i.

p_{ijk} is calculated analogously to (6.15). Using (6.21) and (6.22), the probability of no violation of any standard from outfall k, source i is

$$p_{ik} = \begin{cases} \Pi\, p_{ijk} & ; \quad \text{uncorrelated constituents} \\ \min p_{ijk} & ; \quad \text{correlated constituents} \end{cases} \qquad (6.25)$$

The probability of no violation from any pollutant of any outfall for the source i is then

$$P_i = \prod_k P_{ik} \tag{6.26}$$

where we have assumed that the pollutant loadings in the outfalls are independent. Expected damage and probability of violation have been calculated for a source having many outfalls. The "cost" of undetected violations for this source can then be calculated using (6.20).

Example

In this subsection the "cost" of undetected violations is calculated for a simple case. Consider a single source having two constituents: suspended solids and BOD_5. The various parameters needed to calculate the "cost" are given in Table 6.3. Figures 6.4 and 6.5 give, respectively, the density functions for suspended solids and BOD_5. The probability of violating the effluent standard is the area under the density curve in the region to the right of the effluent standard. This area is shaded in the figures. For this example, the probability of violating the standards for suspended solids is 26% and for BOD_5, 12%.

The relation between the downstream concentration CO (in mg/l) and the example parameters is of the form

$$CO = aM + b \tag{6.27}$$

where M is the mass loading. The formulas for a and b are given in Appendix C. For suspended solids

$$a = \frac{1}{QU + QS} = 0.83$$

and

$$b = CU\left(\frac{QU}{QU + QS}\right) = 0$$

and for dissolved oxygen

$$a = -K_{BOD-DO}/(QU + QS) = -0.42$$

Table 6.3 EXAMPLE PARAMETERS

Parameter	Suspended solids	BOD_5
Upstream flow - QU	1.0 Ml/day	1.0 Ml/day
Effluent flow - QS	0.2 Ml/day	0.2 Ml/day
Distribution	Lognormal	Normal
Mean of Loading - μ	1.5 log kg	1.5 kg
Stan. Dev. of Loading - σ	0.3 log kg	0.5 kg
Effluent Standard - τ	50 kg	2.5 kg
DO concentration of effluent - CS	-	4 mg/l
BOD_5-DO transfer coefficient - K_{BOD-DO}	-	0.5
Assumed upstream concentration - CU	0	0
Assumed upstream concentration of DO	-	9 mg/l

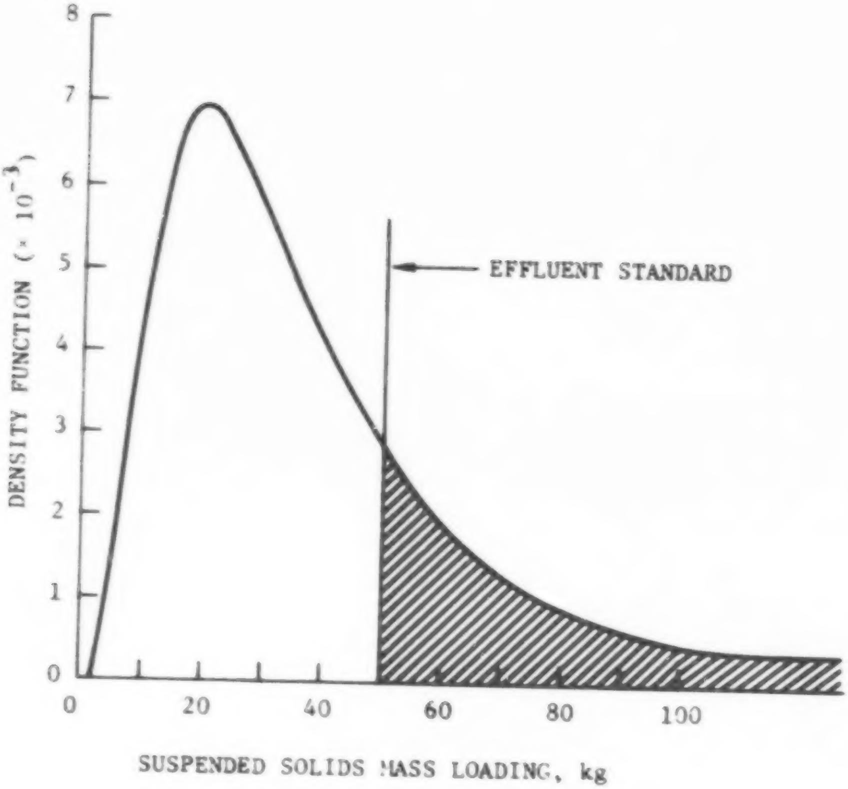

Figure 6.4 Example of density function for suspended solids

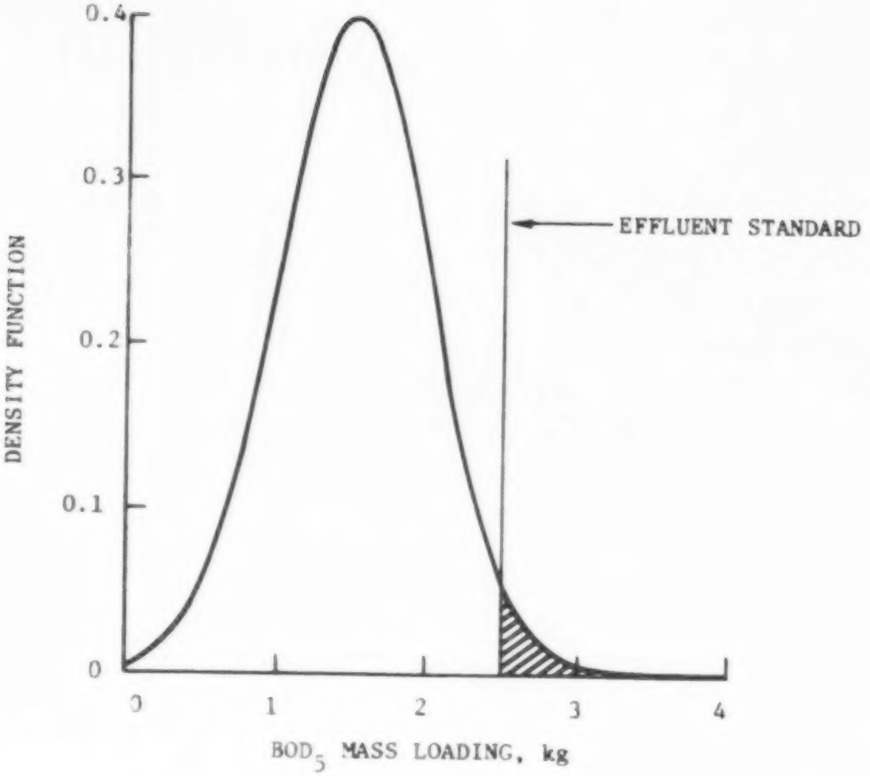

Figure 6.5 **Example of density function for BOD$_5$.**

and

$$b = \frac{1}{QU + QS}(CS_{DO}QS + CU_{DO}QU) - K_{BOD-DO}\ CU_{BOD}$$

$$= 8.2$$

Figure 6.6 shows the density function for CO, the concentration of suspended solids downstream from the source. Also shown is the damage function for suspended solids (note that the ordinate of the density function is not shown). The expected damage is just the area under the product of the density and damage function curves (see (6.12)). For this case the expected damage is 2.86. Figure 6.7 similarly shows the density and damage functions for dissolved oxygen. The expected damage resulting is 1.33. Therefore, we have the expected damage and probability of violation for these two parameters. Assume that the daily variations of the parameters are independent; then the probability, p_i, that the source will not be in violation is the product of the probabilities that each parameter will not be in violation (see (6.21)), or

$$p_i = (1-0.26) \times (1-0.88)$$
$$= 0.65$$

The expected damage from the source, c_i, is the maximum of the damages due to the individual constituents (6.13), so

$$c_i = \max\{2.86, 1.33\}$$

$$= 2.86$$

The "cost" of undetected violations for source i, given that the source was sampled s_i times, is

$$c_i(s_i) = c_i p_i^{s_i} \qquad (6.28)$$

Table 6.4 shows how the "cost" decreases, for this example, as the number of visits, s_i, increases.

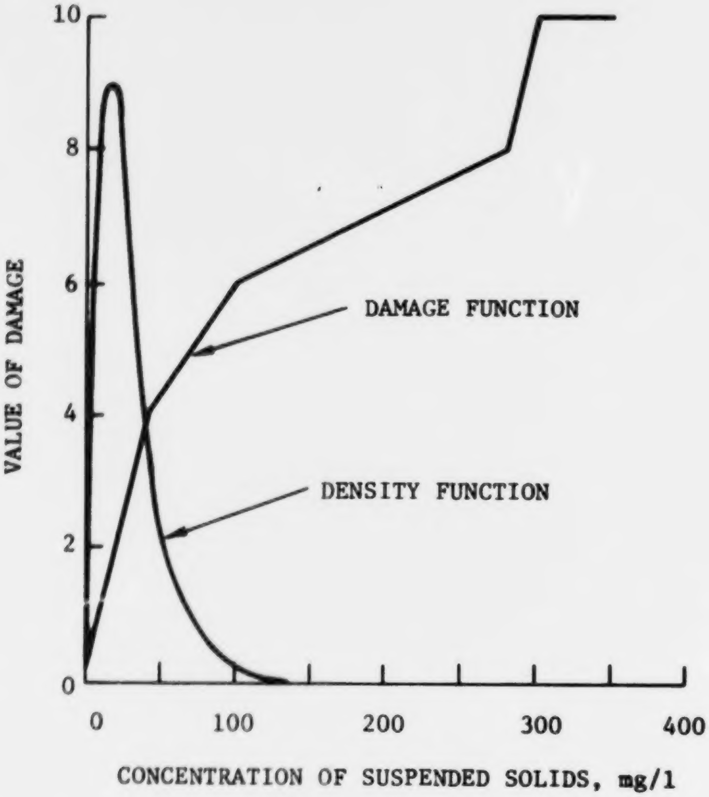

Figure 6.6 Density function and damage function for concentration of suspended solids in stream.

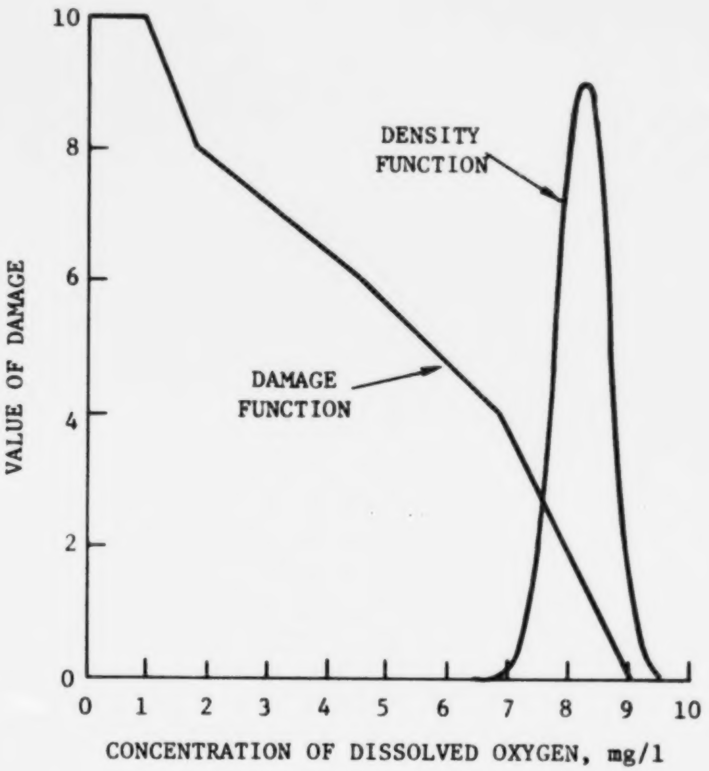

Figure 6.7 **Density function and damage function for concentration of dissolved oxygen in stream.**

Table 6.4 "COST" VERSUS NUMBER OF SAMPLES FOR EXAMPLE

s_i	"Cost" of undetected violations
0	2.86
1	1.86
2	1.23
3	0.80
4	0.52
5	0.34

SECTION VII

RESOURCE ALLOCATION PROBLEM

In the previous section, a performance criterion for the procedure of allocating monitoring resources was defined. This section defines the complete resource allocation problem and describes a method of solution - maximum marginal return.

VII.1 FORMULATION OF PROBLEM

There are three resource allocation problems that the monitoring agency might want solved:

1) Given a certain amount of resources (i.e. budget), determine how the monitoring resources should be allocated to minimize the "cost" of undetected violations.
2) In setting up a monitoring program, determine what level of resources is needed to insure that the "cost" of undetected violations is below a given level.
3) Given an increment of resources, determine how to allocate these additional resources and the resulting improvement in the monitoring system performance.

In the remainder of this subsection, these problems are formulated mathematically.

The "cost" of undetected violations (from Section VI.3) is

$$C(\underline{s}) = \sum_{i=1}^{n_s} C_i(s_i) \qquad (7.1)$$

where $\underline{s} = (s_1, s_2, \ldots, s_{n_s})$,

$$C_i(s_i) = c_i p_i^{s_i} \qquad (7.2)$$

c_i is the expected damage for the i^{th} source, p_i is the probability no violation is observed at the i^{th} source, n_s is the number of sources, and s_i is the number of times the i^{th} source is monitored. The total cost to monitor all the sources where the i^{th} source is monitored s_i times is

$$R(s) = \sum_{i=1}^{n_s} r_i s_i \qquad (7.3)$$

where r_i is the cost of monitoring source i once. r_i is made up of manpower, transportation, equipment and laboratory costs. The actual values of these costs will vary from agency to agency and as a function of time; they are therefore not specified in this report. r_i, however, is calculated for the demonstration case; see Section IX and Appendix D.

Upper and lower bounds on s_i may also be given, i.e.

$$\ell_i \leq s_i \leq L_i \qquad (7.4)$$

To see where a monitor may desire to do this, consider the case where, from ambient monitoring, it has been observed that in a certain reach the level of a particular constituent is higher than usual. Then, one might want to check at least once during the next period all the effluent sources that might have caused this. In this case a lower bound of unity is set on the corresponding sampling rates. Also, consider the case of an effluent having a small expected violation cost. Based upon the existing information, it will have a low priority for being monitored. In order to prevent information from becoming obsolete, one can stipulate that it has to be monitored at least once during a certain period of time. An upper bound might be desired if the monitor does not want to sample any source more than a given number of times. This would be true, for example, if the monitor were required to visit a certain number of sources. Another situation can occur when there is a known polluter (e.g., one against which there are sufficient data to initiate legal action or one which is improving its treatment according to an approved long-term plan); the monitor may then decide not to survey this source frequently because the result is predictable. In this case, the upper bound for s_i would be set to some specified value.

The three optimization problems can now be specified. Problem 1 is

$$\begin{aligned} &\text{minimize } C(\underline{s}) \\ &\text{subject to } R(\underline{s}) \le B \\ &\underline{\ell} \le \underline{s} \le \underline{L} \end{aligned} \qquad \text{(P1)}$$

where B is the monitoring agency's budget and $\underline{\ell} = (\ell_1,\ldots,\ell_{n_s})$ and $\underline{L} = (L_1,\ldots,L_{n_s})$ are upper and lower bounds. Problem 2 is

$$\begin{aligned} &\text{minimize } R(\underline{s}) \\ &\text{subject to } C(\underline{s}) \le A \\ &\underline{\ell} \le \underline{s} \le \underline{L} \end{aligned} \qquad \text{(P2)}$$

where A is the maximum "cost" of undetected violations allowed. Problem 3 is of the same form as Problem 1, except B includes the additional resources and $\underline{\ell}$ specifies the sampling frequencies under the original allocation. The decrease in "cost" between when the original budget is used and the new budget is used is the system improvement. The additional samples specify where to use the additional resources.

VII.2 METHOD OF MAXIMUM MARGINAL RETURN

The optimization method used to solve the resource allocation problems is the method of maximum marginal return. It is particularly suited for these problems since it solves all three problems in the same manner.

The features of the method of maximum marginal return are:

(1) It is very fast on the computer. The computation time grows only proportionally with the size of the problem.

(2) If the function to be minimized is convex, this method will yield the absolute minimum when the cost of resource quanta is equal.

The cost C(s) can be easily shown to be convex--its second derivative is strictly positive for $s_i < N$ (which is always the case) and $p_i < 1$ (this is also satisfied, since p_i is a probability). The only condition that is not satisfied for Problem 1 is the requirement that cost of the quanta, r_i, be equal. However, the method will yield nearly the optimum allocation if

$$\max \; r_i << B \tag{7.5}$$

i.e., the largest cost of a sample is much smaller than the total budget B. Then the difference between the solution obtained by this method and the absolute minimum is negligible. Since (7.5) will be satisfied for the monitoring resource allocation problem, the maximum marginal return method is well suited for determining the sampling rates.

The method of maximum marginal return is basically a steepest descent algorithm. It is based on the following intuitive idea: the best place to allocate one unit of resource is where the marginal return (the decrease in cost - in our case undetected violation "cost" - accrued by using that unit of resource) is greatest. Therefore, by ordering the marginal returns in descending order, one obtains a priority list with the items having highest priority on top.

To be precise, the marginal return accrued when the sampling time on the i^{th} source is increased from s_i-1 to s_i is

$$\mu_i(s_i) = \frac{C_i(s_i-1) - C_i(s_i)}{r_i} \tag{7.6}$$

In view of the convexity of C_i, these marginal returns are monotonically decreasing with s_i, i.e.,

$$\mu_i(s_i) > \mu_i(s_i + 1) \tag{7.7}$$

The priorities of allocation are obtained by simply ordering these marginal returns. If the ordering obtained is, for example,

$$\mu_2(1) > \mu_1(1) > \mu_2(2) > \mu_3(1) \quad .... \tag{7.8}$$

then effluent 2 is sampled with highest priority, then effluent 1, then again effluent 2, then effluent 3, etc. Following this, a relation between the minimized "cost" of undetected violations and the corresponding resource cost is obtained. Therefore, this method solves simultaneously the problem of minimizing the undetected violation "cost" subject to the total budget and the minimization of the budget subject to a given "cost" of undetected violations.

The problem of allocating an increment of resources to maximize the improvement in an existing monitoring system is solved as follows: Set up the priority list as described above, and remove from the list those samples that have been allocated. The remaining items on the list are, in descending priority, the ones that should be monitored with an increase in resources.

The above method will be illustrated via a simple numerical example. Assume there are n_s=3 pollutant sources with "costs" of undetected violation (for the period in consideration) as given in Table 7.1. It is assumed, for the purpose of this example, that costs of monitoring each of these effluents are the same (equal to one).

The "costs" C_i of undetected violations are given in these tables as functions of the corresponding number of samples. The maximum number of samples per source is taken as 5. Also the marginal returns as defined in (7.6) and the priority ordering according to (7.8) appear next to each sample.

The priority list of the sources sampled appears in Table 7.2 together with the "cost" of undetected violations as a function of the available resources. This table shows immediately the necessary resources to achieve a given "cost" of undetected violations and also the achievable minimum "cost" of undetected violations for a given amount of resources (number of samples).

As an example of Problem 1, consider the problem of finding the best allocation of 6 samples. From column 2 of Table 7.2, one sees that the 6 samples should be taken from sources 3, 2, 1, 3, 1, and 2. The sampling frequencies are then $s_1 = 2$, $s_2 = 2$, $s_3 = 2$. From column 3 of Table 7.2, the "cost" corresponding to these frequencies is 1.16.

As an example of Problem 2, consider the problem of finding the minimum amount of resources required to bring the "cost" of undetected violations to 1.00 or less. From column 3 of Table 7.2, one sees that the first time that the "cost" drops below 1.00 occurs for 7 samples, for

Table 7.1 "COST" OF UNDETECTED VIOLATIONS AND PRIORITY ORDERING

Number of samples	"Cost" undetected violations	Marginal return	Priority order
s_1	c_1	μ_1	
0	1.00		
1	0.70	0.30	3
2	0.45	0.25	5
3	0.25	0.20	7
4	0.08	0.17	8
5	0.02	0.06	14
s_2	c_2	μ_2	
0	1.00		
1	0.65	0.35	2
2	0.42	0.23	6
3	0.27	0.15	9
4	0.15	0.12	11
5	0.08	0.07	13
s_3	c_3	μ_3	
0	1.00		
1	0.55	0.45	1
2	0.29	0.26	4
3	0.15	0.14	10
4	0.05	0.10	12
5	0.01	0.04	15

which the cost is 0.96. From column 2 of this table one sees that the 7 samples should be taken, in order, from sources 3, 2, 1, 3, 1, 2, and 1. The corresponding sampling frequencies are thus $s_1 = 3$ (three samples at source 1), $s_2 = 2$ (two samples at source 2), and $s_3 = 2$ (two samples at source 3).

As an illustration of how to use the information to allocate additional resources to improve an existing monitoring system (Problem 3), assume that the preassigned sampling frequencies are

$$s_1 = 1, \; s_2 = 2, \; s_3 = 1$$

Consider the problem of optimally allocating four more samples. This is solved as follows: Take the priority list and omit the first s_i samples on source i, as illustrated in Table 7.3. Then it is seen that the priorities for the additional four samples are: first source #3, then #1, again #1, and again #1. The resulting overall sampling frequencies are

$$s_1 = 4, \; s_2 = 2, \; s_3 = 2.$$

Table 7.3 ALLOCATION OF ADDITIONAL INCREMENTS OF RESOURCES TO A GIVEN MONITORING SYSTEM

Original priority list of sources	Priority list of sources given the preassigned samples
3	
2	
1	
3	3
1	1
2	
1	1
1	1
2	2
3	3
2	2
3	3
2	2
1	1
3	3

SECTION VIII

RESOURCE ALLOCATION PROGRAM

Components of the allocation procedure were described in the previous three sections. This section discusses how these components fit together to form the Resource Allocation Program. Examples are also given showing the operation of the Program.

VIII.1 GENERAL PROGRAM DESCRIPTION

A flowchart of the Resource Allocation Program is shown in Figure 8.1. The following is a brief description of the function on the various components.

(1) Initialize Statistical Description

Combine the raw self-monitoring and compliance monitoring data to obtain an initial statistical description (distribution, mean and standard deviation) for each pollutant of each source.

(2) Calculate Expected Damage and Probability of Violation

Use the statistical description of the effluent loads, the effluent standards, and the stream parameters to obtain the expected damage and probability of violation for each source.

(3) Determine Priorities

Use the method of maximum marginal return to obtain the monitoring frequencies.

RESOURCE ALLOCATION PROGRAM

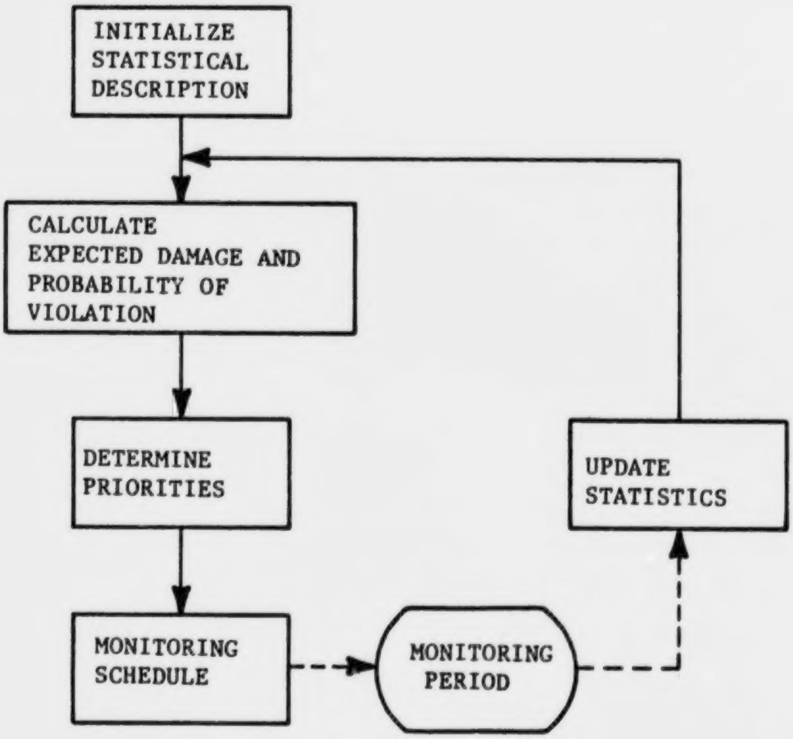
INITIALIZE STATISTICAL DESCRIPTION
CALCULATE EXPECTED DAMAGE AND PROBABILITY OF VIOLATION
DETERMINE PRIORITIES
MONITORING SCHEDULE
MONITORING PERIOD
UPDATE STATISTICS

Figure 8.1 Flow of Resource Allocation Program.

(4) Monitoring Schedule

Take the sampling frequencies obtained in the previous component and determine which day to sample which sources.

(5) Monitoring Period

This box represents the actual time spent monitoring the sources.

(6) Update Statistics

Combine new self-monitoring and compliance data with the initial statistics to obtain an updated statistical description of the effluents.

All the components except the "Monitoring Schedule" have been described in detail in Sections V, VI, and VII. The scheduling of the sampling depends on a number of factors which are difficult to quantify in an optimization framework, such as: the spatial location of the various effluent sources, the size of the monitoring agency's jurisdiction, and the availability of personnel. This scheduling is beyond the scope of this report.

Figure 8.2 gives a more detailed description of the Resource Allocation Program. It describes in detail what data are needed by each component of the Program. The basic output of the Program is the priorities and the monitoring frequencies.

VIII.2 SIMPLIFIED EXAMPLE

The performance of the Resource Allocation Program is demonstrated in this section, using a simplified example. Initially, it is assumed that there are four sources to be monitored, each having four months of self-monitoring data available from which to obtain the initial statistics.

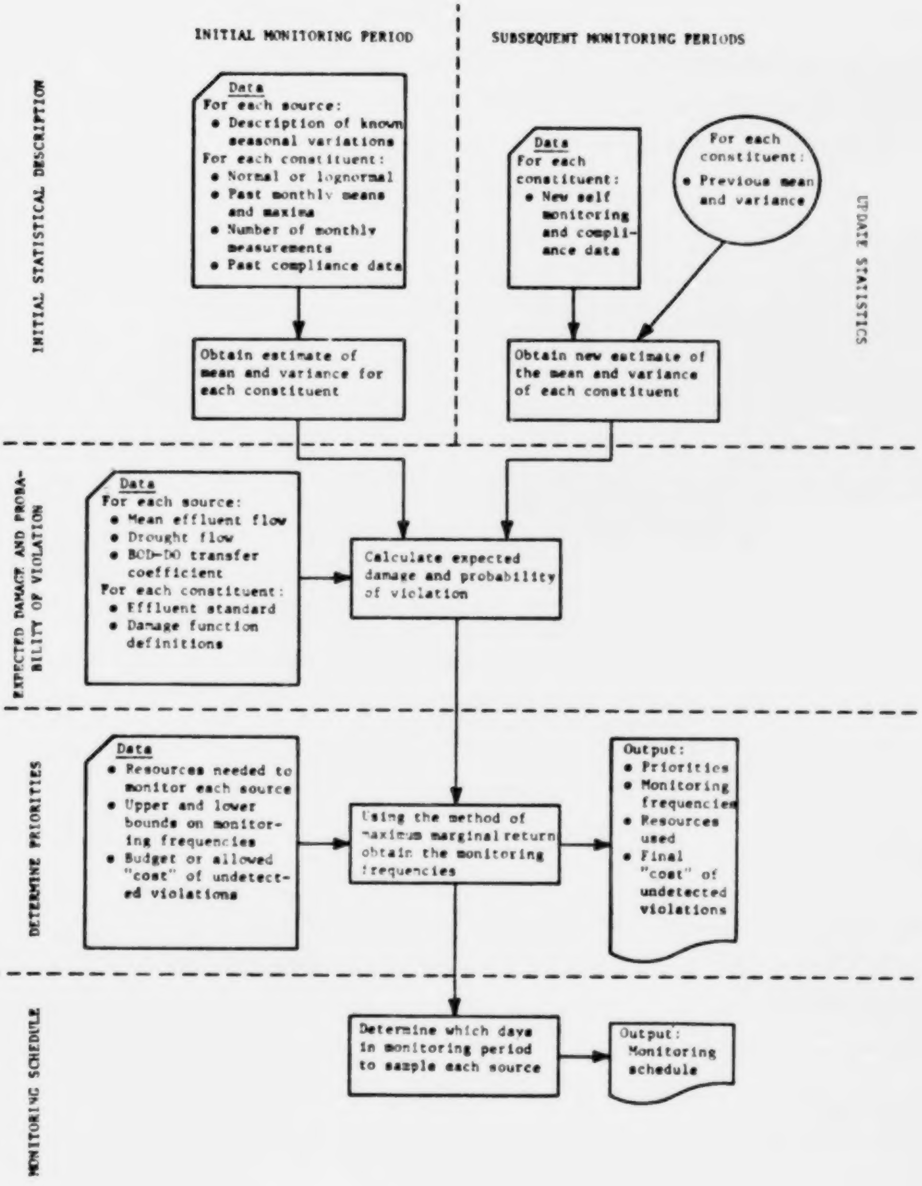
INITIAL MONITORING PERIOD
SUBSEQUENT MONITORING PERIODS
INITIAL STATISTICAL DESCRIPTION
Data
For each source:
• Description of known seasonal variations
For each constituent:
• Normal or lognormal
• Past monthly means and maxima
• Number of monthly measurements
• Past compliance data
Data
For each constituent:
• New self monitoring and compliance data
For each constituent:
• Previous mean and variance
UPDATE STATISTICS
Obtain estimate of mean and variance for each constituent
Obtain new estimate of the mean and variance of each constituent
EXPECTED DAMAGE AND PROBABILITY OF VIOLATION
Data
For each source:
• Mean effluent flow
• Drought flow
• BOD-DO transfer coefficient
For each constituent:
• Effluent standard
• Damage function definitions
Calculate expected damage and probability of violation
DETERMINE PRIORITIES
Data
• Resources needed to monitor each source
• Upper and lower bounds on monitoring frequencies
• Budget or allowed "cost" of undetected violations
Using the method of maximum marginal return obtain the monitoring frequencies
Output:
• Priorities
• Monitoring frequencies
• Resources used
• Final "cost" of undetected violations
MONITORING SCHEDULE
Determine which days in monitoring period to sample each source
Output:
Monitoring schedule

Figure 8.2 Resource allocation program.

The initial self monitoring data assumed are shown in Tables 8.3a through 8.3e. The data have been abstracted from real data that were used for the demonstration case (Section IX). Using the procedure outlined in Section V.3, Tables 8.4a through 8.4e present the initial statistics obtained from the data. The estimated mean and estimated standard deviation are the monthly estimates using the techniques developed in Appendix A. For Source 4, the sample size of the effluent constituents for a single month is 2; therefore, the data in months 1 and 2 and months 3 and 4 have to be aggregated, as discussed in Section V.2. Thus, only two estimates of the mean and two of the variance are given in Table 8.4d and 8.4e. Tables 8.4a through 8.4e also show how the estimates of the mean and standard deviation are sequentially updated as the monthly estimates are combined to obtain the estimates to be used in the Resource Allocation Program. For this case the design parameters k_n and k_ν, which determine the degree of the discounting of past information, have been set to 3.* The updated mean and variance for month 2 are therefore the combined estimates derived from the 1st and 2nd monthly estimates. The updated mean and variance for month 3 are the combination of the updated estimates for month 2 and monthly estimate for month 3. The same process is repeated for month 4, yielding the initial statistical description to be used in the program.

The expected damage and probability of violation obtained from the data are shown in Table 8.5, along with the estimated source flow and the stream flow. For this case, the upstream concentration was assumed to be at a level causing zero damage, and the distributions of the various parameters were assumed uncorrelated. Certain of the entries deserve some comment. Source 3 is a large sewage treatment plant. From the table, the impact of BOD_5 and phosphates is large; however, the standards are also large and therefore the probability of violation for the parameters is small. Source 4 has a relatively small impact on the stream (i.e., small expected damage); however, the standards have been set so that the probability of violation is very large. The resources required

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* k_n and k_ν are discussed in Section V.2. The effect of changing k_n and k_ν is shown in VIII.3.

Table 8.3a SELF MONITORING DATA FOR SOURCE 1

Month	Mean source flow, Ml/day	Parameter: pH Max Eff. standard: 9 Distribution: Normal			Parameter: pH Min Eff. standard: 6 Distribution: Normal			Parameter: Lead Eff. standard: 2 kg Distribution: Normal		
		Mean	Max	Sample size	Mean	Min	Sample size	Mean, kg	Max, kg	Sample size
1	0.90	8.5	10.6	20	8.5	6.0	20	0.41	1.0	20
2	1.10	7.6	9.0	22	7.6	5.4	22	1.08	1.7	22
3	1.20	8.3	9.8	22	8.3	6.4	22	1.09	6.3	22
4	0.85	8.1	9.5	20	8.1	6.4	20	0.52	1.8	22

Table 8.3b SELF MONITORING DATA FOR SOURCE 2

Month	Mean source flow, Ml/day	Parameter: Chromium Eff. standard: 0.45 kg Distribution: Normal			Parameter: Copper Eff. standard: 1.5 kg Distribution: Lognormal			Parameter: Fluoride Eff. standard: 30 kg Distribution: Normal		
		Mean, kg	Max, kg	Sample size	Mean, kg	Max, kg	Sample size	Mean kg	Max, kg	Sample size
1	0.80	0.216	0.808	18	0.524	1.89	18	24.4	31.4	18
2	0.78	0.313	0.867	19	0.374	1.87	19	25.4	31.9	19
3	0.87	0.214	0.620	21	0.364	1.25	22	24.7	31.0	22
4	0.85	0.132	0.255	14	0.110	0.42	14	14.0	31.0	11

Table 8.3c SELF MONITORING DATA FOR SOURCE 3

Month	Mean source flow, Ml/day	Parameter: BOD_5 Eff. standard: 3500 kg Distribution: Normal			Parameter: Phosphate Eff. standard: 500 kg Distribution: Lognormal			Parameter: Sus. Solids Eff. standard: 4050 kg Distribution: Lognormal			Parameter: Dissolved oxygen	
		Mean, kg	Max, kg	Sample size	Mean, kg	Max, kg	Sample size	Mean, kg	Max, kg	Sample size	Mean, mg/l	Sample size
1	105	1165	2115	30	178	658	30	2430	6030	30	3.9	30
2	110	900	2115	31	171	338	31	1665	5130	31	3.8	31
3	109	1395	2880	30	171	500	30	3240	10935	30	4.2	30
4	108	1080	2385	31	88	275	31	2160	4590	31	4.1	31

Table 8.3d SELF MONITORING DATA FOR SOURCE 4, PIPE 1

Month	Mean source, flow Ml/day	Parameter: Phosphates Eff. standard: 0.6 kg Distribution: Normal			Parameter: Sus. Solids Eff. standard: 25 kg Distribution: Normal		
		Mean, kg	Max, kg	Sample size	Mean, kg	Max, kg	Sample size
1	0.35	0.15	0.24	2	12.0	18.9	2
2	0.26	0.30	0.36	2	14.6	18.9	2
3	0.29	0.31	0.36	2	16.4	18.0	2
4	0.30	1.20	2.56	2	11.0	15.3	2

Table 8.3e SELF MONITORING DATA FOR SOURCE 4, PIPE 2

Month	Mean source flow, Ml/day	Parameter: Phosphates Eff. standard: 3.5 kg Distribution: Normal			Parameter: Sus. Solids Eff. standard: 80 kg Distribution: Normal		
		Mean, kg	Max, kg	Sample size	Mean, kg	Max, kg	Sample size
1	0.90	2.9	3.2	2	158	296	2
2	1.01	3.5	3.9	2	18	26	2
3	1.09	2.9	3.1	2	93	145	2
4	1.00	5.8	9.8	2	31	33	2

Table 8.4a INITIAL STATISTICS FOR SOURCE 1

Month	Parameter: pH Max Distribution: Normal				Parameter: pH Min Distribution: Normal				Parameter: Lead Distribution: Normal			
	Est. mean	Est. st. dev.	Updated mean	Updated st. dev.	Est. mean	Est. st. dev.	Updated mean	Updated st. dev.	Est. mean,kg	Est. st. dev.,kg	Updated mean, kg	Updated st. dev.,kg
1	8.5	1.12	-	-	8.5	1.33	-	-	0.41	0.31	-	-
2	7.6	0.73	8.03	1.06	7.6	1.15	8.03	1.33	1.08	0.32	0.76	0.51
3	8.3	0.78	8.12	0.98	8.3	0.99	8.12	1.22	1.09	2.72	0.87	1.62
4	8.1	0.74	8.12	0.92	8.1	0.90	8.12	1.14	0.515	0.67	0.78	1.45

Table 8.4b INITIAL STATISTICS FOR SOURCE 2

Month	Parameter: Chromium Distribution: Normal				Parameter: Copper Distribution: Lognormal				Parameter: Fluoride Distribution: Normal			
	Est. mean, kg	Est. st. dev., kg	Updated mean, kg	Updated st. dev., kg	Est. mean, log kg	Est. st.dev., log kg	Updated mean, log kg	Updated st. dev., log kg	Est. mean, kg	Est. st.dev., kg	Updated mean, kg	Updated st. dev., kg
1	0.216	0.321	-	-	-0.437	0.369	-	-	24.4	3.79	-	-
2	0.313	0.297	0.266	0.308	-0.685	0.474	-0.565	0.443	25.4	3.49	24.9	3.62
3	0.214	0.214	0.247	0.277	-0.570	0.337	-0.567	0.403	24.7	3.29	24.8	3.46
4	0.132	0.070	0.218	0.246	-1.146	0.404	-0.711	0.502	24.0	4.17	24.6	3.61

Table 8.4c INITIAL STATISTICS FOR SOURCE 3

Month	Parameter: BOD$_5$ Distribution: Normal				Parameter: Phosphate Distribution: Lognormal				Parameter: Suspended Solids Distribution: Lognormal				Parameter: Dissolved oxygen	
	Est. mean, kg	Est. st.dev., kg	Updated mean, kg	Updated st.dev., kg	Est. mean, log kg	Est. st.dev., log kg	Updated mean, log kg	Updated st.dev., log kg	Est. mean, log kg	Est. st.dev., log kg	Updated mean, log kg	Updated st.dev., log kg	Est. mean, mg/l	Updated mean, mg/l
1	1165	470	---	---	2.12	0.339	---	---	3.33	0.218	---	---	3.90	---
2	900	598	1030	555	2.20	0.157	2.16	0.265	3.13	0.282	3.23	0.277	3.80	3.85
3	1395	734	1150	648	2.12	0.268	2.16	0.264	3.40	0.312	3.29	0.302	4.20	3.96
4	1080	642	1133	643	1.85	0.286	2.08	0.313	3.30	0.175	3.29	0.274	4.10	4.00

Table 8.4d INITIAL STATISTICS FOR SOURCE 4, PIPE 1

Month	Parameter: Phosphates Distribution: Normal				Parameter: Suspended Solids Distribution: Normal			
	Est. mean, kg	Est. st.dev., kg	Updated mean, kg	Updated st.dev., kg	Est. mean, kg	Est. st.dev., kg	Updated mean, kg	Updated st. dev., kg
1	-	-	-	-	-	-	-	-
2	0.225	0.101	-	-	13.3	4.21	-	-
3	-	-	-	-	-	-	-	-
4	0.755	1.356	0.490	0.925	13.7	3.23	13.5	3.38

Table 8.4e INITIAL STATISTICS FOR SOURCE 4, PIPE 2

Month	Parameter: Phosphates Distribution: Normal				Parameter: Suspended Solids Distribution: Normal			
	Est. mean, kg	Est. st.dev., kg	Updated mean, kg	Updated st.dev., kg	Est. mean, kg	Est. st.dev., kg	Updated mean, kg	Updated st.dev., kg
1	-	-	-	-	-	-	-	-
2	3.20	0.526	-	-	88.0	156.3	-	-
3	-	-	-	-	-	-	-	-
4	4.35	4.096	3.78	2.719	62.0	62.3	75.0	108.2

Table 8.5 EXPECTED DAMAGE AND PROBABILITY OF VIOLATION

Source	Pipe	Est. source flow, Ml/day	Stream flow, Ml/day	Parameter	Expected damage, D_{ij}	Probability of no violation, P_{ij},%	Expected damage for source, C_i	Probability of no violation for source, P_i,%
1	1	0.961	100	pH	0.29	80.0		
				Lead	1.60	80.0	1.60	64.0
2	1	0.845	320	Chromium	0.08	82.6		
				Copper	0.12	96.1		
				Fluoride	0.00	93.1	0.12	74.0
3	1	108	525	BOD_5	3.22	100.0		
				Phosphate	3.64	97.6		
				Suspended Solids	0.37	87.8	3.64	85.6
4	1	0.297	300	Phosphates	-	100.0		
				Suspended Solids	-	51.8		
	2	1.016		Phosphates	0.29	54.4		
				Suspended Solids	0.03	46.0	0.29	13.0

to sample the sources are given in Table 8.6, and the priority list is given in Table 8.7. For the purposes of this example, it was assumed that the sources could be sampled between 0 and 10 times. From the table, one sees that Sources 1 and 3 should be sampled with higher priority than Sources 2 and 4. This is due to the much larger expected damage from the former sources. Source 4 appears relatively early in the list, but most of the samples have low priority. This is because the probability of violation is very large and therefore the chances are that the source will be caught in violation after one or two visits. Further sampling is therefore not necessary. Source 2 has a small expected damage and a fairly large probability of no violation resulting in a low sampling priority. Table 8.7 also gives the marginal return, "cost" of undetected violations and resources used. The marginal returns are decreasing (the list has been ordered in just this manner). The "cost" of undetected violations is decreasing, and the resources required are increasing as more sources are sampled.

If only, say, $10,000 were available for monitoring, then only the sources with priority 1 through 18 would be monitored. The sampling frequencies for this case are shown in Table 8.8. If, on the other hand, a maximum allowed "cost" of undetected violations of, say, 1.0 were specified, then sources with priorities 1 through 19 would be sampled. The sampling frequencies for this case are shown in Table 8.9. The priority list in Table 8.7 also shows when the return from monitoring (i.e. the marginal return) starts becoming negligible; the return, in this case, for monitoring more than, say, 25 sources is very small.

VIII.3 SENSITIVITY STUDIES

This subsection investigates the effect of various changes in the inputs and design parameters of the example just discussed.

Table 8.6. RESOURCES NEEDED TO SAMPLE

Source	Field and office costs	Laboratory costs	Total Cost r_i
1	\$525	\$10.50	\$535.50
2	\$525	\$23.00	\$548.00
3	\$525	\$38.00	\$563.00
4	\$525	\$30.00	\$555.00

Table 8.7 PRIORITY LIST OF SAMPLES FOR SIMPLIFIED EXAMPLE

PRIORITY	SOURCE SAMPLED	MARGINAL RETURN X100	COST OF UNDETECTED VIOLATIONS	RESOURCES REQUIRED
1	1	.10774492	5.07571	535.50
2	3	.09326524	4.55342	1095.50
3	3	.07989130	4.10603	1655.50
4	1	.06899248	3.73658	2191.00
5	3	.06843515	3.35334	2751.00
6	3	.05862177	3.02506	3311.00
7	3	.05021559	2.74385	3871.00
8	4	.04526206	2.49264	4426.00
9	1	.04417806	2.25607	4961.50
10	3	.04301484	2.01519	5521.50
11	3	.03684665	1.80885	6081.50
12	3	.03156296	1.63209	6641.50
13	1	.02828861	1.48061	7177.00
14	3	.02703693	1.32920	7737.00
15	3	.02315992	1.19951	8297.00
16	1	.01811409	1.10251	8832.50
17	1	.01159902	1.04039	9368.00
18	1	.00742722	1.00062	9903.50
19	4	.00590254	.96766	10458.50
20	2	.00556719	.93735	11006.50
21	1	.00475588	.91199	11542.00
22	2	.00412025	.88931	12090.00
23	2	.00304938	.87260	12638.00
24	1	.00304534	.85629	13173.50
25	2	.00225693	.84392	13721.50
26	1	.00195003	.83348	14257.00
27	2	.00167027	.82432	14805.00
28	2	.00123616	.81755	15353.00
29	2	.00091488	.81254	15901.00
30	4	.00076974	.80826	16456.00
31	2	.00067710	.80455	17004.00
32	2	.00050112	.80181	17552.00
33	2	.00037087	.79978	18100.00
34	4	.00010038	.79922	18655.00
35	4	.00001309	.79915	19210.00
36	4	.00000171	.79914	19765.00
37	4	.00000022	.79914	20320.00
38	4	.00000003	.79914	20875.00
39	4	.00000000	.79914	21430.00
40	4	.00000000	.79914	21985.00

Table 8.8 FINAL ALLOCATION GIVEN MONETARY BUDGET

```
                              FINAL ALLOCATION

                              BUDGET  10000.00

         MIN NO.   MAX NO.                                 COST OF
         SAMPLES   SAMPLES    TIMES     RESOURCES         UNDETECTED
SOURCE  REQUIRED   ALLOWED    SAMPLED      USED           VIOLATIONS
-----------------------------------------------------------------------


   1           0       10          7      3748.50            .07081
   2           0       10          0          .00            .11738
   3           0       10         10      5600.00            .77476
   4           0       10          1       555.00            .03767

-----------------------------------------------------------------------

TOTAL RESOURCES USED  9903.50
FINAL COST OF UNDETECTED VIOLATIONS   1.00062
```

Table 8.9 FINAL ALLOCATION GIVEN MAXIMUM ALLOWED COST OF UNDETECTED VIOLATIONS

```
                              FINAL ALLOCATION

MAXIMUM ALLOWED COST OF UNDETECTED VIOLATIONS   1.00000

         MIN NO.   MAX NO.                                 COST OF
         SAMPLES   SAMPLES    TIMES     RESOURCES         UNDETECTED
SOURCE  REQUIRED   ALLOWED    SAMPLED      USED           VIOLATIONS
-----------------------------------------------------------------------


   1           0       10          7      3748.50            .07081
   2           0       10          0          .00            .11738
   3           0       10         10      5600.00            .77476
   4           0       10          2      1110.00            .00491

-----------------------------------------------------------------------

TOTAL RESOURCES USED 10458.50
FINAL COST OF UNDETECTED VIOLATIONS    .96786
```

Distribution

In order to check the sensitivity of the normal assumption versus log-normal assumption in the distribution of pollutants, the loadings of phosphate and suspended solids in Source 3 are now assumed normally distributed. (The self monitoring data are given in Table 8.3c. They are identical to the previous example.) The expected damage and probability of no violation for phosphates are now 3.53 and 98.5% respectively, and the expected damage and probability of no violation for suspended solids are 0.41 and 76.0% respectively. These numbers can be compared with the analagous values in Table 8.5. The major difference is in the suspended solids where both the expected damage and probability of violation changed by about 10%. The expected damage for the source is now 3.54 (compared to 3.64), and the probability of no violation for the source is 74.9% (compared to 85.6%). Table 8.10 gives the priority list for this case. The priority ordering is slightly changed. It is therefore seen that changing the distributional form will affect the sampling frequencies by a small, but not negligible, amount.

Correlation

The effect of assuming that the constituents of a source were correlated versus uncorrelated is investigated by first assuming that the constituents of Source 2 are completely correlated. The constituents of the other sources are assumed uncorrelated, as in the original example. The probability of no violation for source 2 is 82.6% as opposed to 74% for the original example. The priority list for this case is given in Table 8.11. Comparing this table with Table 8.7 shows little change - the priorities for source 2 have increased slightly.

Now assume that the constituents for all the sources are completely correlated. The probabilities of no violation for sources 1,2,3 and 4 are 80.0%, 82.6%, 87.8% and 28.9% respectively.

Table 8.10 PRIORITY LIST, CONSTITUENTS IN SOURCE 3 ALL NORMALLY DISTRIBUTED

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```
                      PRIORITY LIST OF SAMPLES

                                                 COST OF
                  SOURCE        MARGINAL       UNDETECTED     RESOURCES
PRIORITY          SAMPLED      RETURN X100     VIOLATIONS      REQUIRED
------------------------------------------------------------------------


    1               3          .15868572        4.65774         560.00
    2               3          .11880537        3.99243        1120.00
    3               1          .10774492        3.41546        1655.50
    4               3          .08894762        2.91735        2215.50
    5               1          .06899248        2.54790        2751.00
    6               3          .06659361        2.17497        3311.00
    7               3          .04985753        1.89577        3871.00
    8               4          .04526206        1.64456        4426.00
    9               1          .04417606        1.40799        4961.50
   10               3          .03732751        1.19896        5521.50
   11               1          .02828861        1.04747        6057.00
   12               3          .02794649         .89097        6617.00
   13               3          .02092307         .77380        7177.00
   14               1          .01811409         .67680        7712.50
   15               3          .01566476         .58909        8272.50
   16               3          .01172795         .52340        8832.50
   17               1          .01159902         .46129        9368.00
   18               1          .00742722         .42152        9903.50
   19               4          .00590254         .38876       10458.50
   20               2          .00556719         .35825       11006.50
   21               1          .00475586         .33278       11542.00
   22               2          .00412025         .31020       12090.00
   23               2          .00304938         .29349       12638.00
   24               1          .00304534         .27718       13173.50
   25               2          .00225683         .26482       13721.50
   26               1          .00195003         .25437       14257.00
   27               2          .00167027         .24522       14805.00
   28               2          .00123616         .23845       15353.00
   29               2          .00091488         .23343       15901.00
   30               4          .00076974         .22916       16456.00
   31               2          .00067710         .22545       17004.00
   32               2          .00050112         .22270       17552.00
   33               2          .00037087         .22067       18100.00
   34               4          .00010038         .22012       18655.00
   35               4          .00001309         .22004       19210.00
   36               4          .00000171         .22003       19765.00
   37               4          .00000022         .22003       20320.00
   38               4          .00000003         .22003       20875.00
   39               4          .00000000         .22003       21430.00
   40               4          .00000000         .22003       21985.00

------------------------------------------------------------------------
```

Table 8.11 PRIORITY LIST, SOURCE 2 CONSTITUENTS CORRELATED

PRIORITY LIST OF SAMPLES

PRIORITY	SOURCE SAMPLED	MARGINAL RETURN X100	COST OF UNDETECTED VIOLATIONS	RESOURCES REQUIRED
1	1	.10774492	5.07571	535.50
2	3	.09326524	4.55342	1095.50
3	3	.07969130	4.10603	1655.50
4	1	.06899248	3.73458	2191.00
5	3	.06843515	3.35334	2751.00
6	3	.05862177	3.02506	3311.00
7	3	.05021559	2.74365	3871.00
8	4	.04526206	2.49264	4426.00
9	1	.04417806	2.25607	4961.50
10	3	.04301484	2.01519	5521.50
11	3	.03664665	1.80855	6081.50
12	3	.03156296	1.63209	6641.50
13	1	.02828861	1.46061	7177.00
14	3	.02703693	1.32920	7737.00
15	3	.02315992	1.19951	8297.00
16	1	.01811409	1.10251	8832.50
17	1	.01159902	1.04039	9368.00
18	1	.00742722	1.00062	9903.50
19	4	.00590254	.96786	10458.50
20	1	.00475588	.94239	10994.00
21	2	.00371715	.92202	11542.00
22	2	.00307210	.90519	12090.00
23	1	.00304534	.88888	12625.50
24	2	.00253898	.87497	13173.50
25	2	.00209836	.86347	13721.50
26	1	.00195003	.85303	14257.00
27	2	.00173423	.84352	14805.00
28	2	.00143328	.83567	15353.00
29	2	.00118456	.82918	15901.00
30	2	.00097899	.82381	16449.00
31	2	.00080910	.81938	16997.00
32	4	.00076974	.81510	17552.00
33	2	.00066870	.81144	18100.00
34	4	.00010038	.81088	18655.00
35	4	.00001309	.81081	19210.00
36	4	.00000171	.81080	19765.00
37	4	.00000022	.81080	20320.00
38	4	.00000003	.81080	20875.00
39	4	.00000000	.81080	21430.00
40	4	.00000000	.81080	21985.00

There is little change between the priority list for this case (Table 8.12) and the original priority list (Table 8.7).

No strong conclusions can be drawn from these examples. Cases can clearly be devised where the priority list will be very sensitive to the correlation assumption. However, from these examples it is seen that in many cases the priorities will be insensitive to this assumption.

Minimizing Number of Undetected Violators

The objective of the Resource Allocation Problem can be changed to minimize the number of undetected violators (no "cost" due to environmental damage) by setting all the expected damages in the priority procedure to one. The statistics and the probability of not violating will be the same as for the original problem. The new priority list is given in Table 8.13. As would be expected, the priority list is very different from that for the case which considered damages.

Discounting Past Data

Past data are discounted by ensuring that the confidence parameters n and ν in the Bayesian update formula do not get too large. This is accomplished by specifying that $n \leq k_n \nu'$ and $\nu \leq k_\nu \nu'$ where n' and ν' are the confidence parameters for the month being used to update the statistics. In the original example $k_n = k_\nu = 3.0$. Let us now assume that $k_n = k_\nu = 1.5$. The initial statistical description will therefore depend more strongly on the data in the months closer to the start of the monitoring period.

Table 8.14 compares the initial statistical description, at the start of monitoring, for the cases when $k_n = k_\nu = 3.0$ and $k_n = k_\nu = 1.5$. By comparing this table with the initial data (Tables 8.3a through 8.3e) it is evident that the data for month 4 are more strongly felt for the case where $k_n = k_\nu = 1.5$ than for the case where $k_n = k_\nu = 3.0$.

Table 8.12 PRIORITY LIST, SOURCES' CONSTITUENTS ALL CORRELATED

```
                        PRIORITY LIST OF SAMPLES

                                              COST OF
                   SOURCE     MARGINAL       UNDETECTED    RESOURCES
PRIORITY           SAMPLED    RETURN X100    VIOLATIONS     REQUIRED
--------------------------------------------------------------------

    1                 3       .07961628       5.20683        560.00
    2                 3       .06967035       4.81556       1120.00
    3                 3       .06131743       4.47218       1680.00
    4                 1       .05966003       4.15163       2215.50
    5                 3       .05361148       3.85028       2775.50
    6                 1       .04769870       3.59379       3311.00
    7                 3       .04722435       3.32933       3871.00
    8                 3       .04144355       3.09725       4431.00
    9                 4       .03895274       2.88106       4986.00
   10                 1       .03832751       2.67581       5521.50
   11                 3       .03637039       2.47214       6081.50
   12                 3       .03191824       2.29340       6641.50
   13                 1       .03066884       2.12917       7177.00
   14                 3       .02801109       1.97230       7737.00
   15                 3       .02458222       1.83464       8297.00
   16                 1       .02454055       1.70323       8832.50
   17                 1       .01963692       1.59807       9368.00
   18                 1       .01571296       1.51393       9903.50
   19                 1       .01257317       1.44660      10439.00
   20                 1       .01006075       1.39273      10974.50
   21                 4       .00980149       1.33833      11529.50
   22                 1       .00805042       1.29522      12065.00
   23                 2       .00371715       1.27485      12613.00
   24                 2       .00307210       1.25801      13161.00
   25                 2       .00253898       1.24410      13709.00
   26                 4       .00246630       1.23041      14264.00
   27                 2       .00209838       1.21891      14812.00
   28                 2       .00173423       1.20941      15360.00
   29                 2       .00143328       1.20155      15908.00
   30                 2       .00118456       1.19506      16456.00
   31                 2       .00097899       1.18970      17004.00
   32                 2       .00080910       1.16526      17552.00
   33                 2       .00066870       1.18160      18100.00
   34                 4       .00062058       1.17816      18655.00
   35                 4       .00015615       1.17729      19210.00
   36                 4       .00003929       1.17707      19765.00
   37                 4       .00000989       1.17702      20320.00
   38                 4       .00000249       1.17700      20875.00
   39                 4       .00000063       1.17700      21430.00
   40                 4       .00000016       1.17700      21985.00

--------------------------------------------------------------------
```

Table 8.13 PRIORITY LIST, MINIMIZE NUMBER OF UNDETECTED VIOLATORS

PRIORITY LIST OF SAMPLES

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PRIORITY	SOURCE SAMPLED	MARGINAL RETURN X100	COST OF UNDETECTED VIOLATIONS	RESOURCES REQUIRED
1	4	.15668323	3.13041	555.00
2	1	.06716497	2.77074	1090.50
3	2	.04742781	2.51084	1635.50
4	1	.04300785	2.26053	2174.00
5	2	.03510111	2.06817	2722.00
6	1	.02753429	1.94070	3257.50
7	2	.02597818	1.79834	3805.50
8	3	.02560657	1.65494	4365.50
9	3	.02193467	1.53211	4925.50
10	4	.02043276	1.41871	5480.50
11	2	.01922634	1.31335	6028.50
12	3	.01878931	1.20813	6588.50
13	1	.01763427	1.11370	7124.00
14	3	.01609498	1.02356	7684.00
15	2	.01422933	.94559	8232.00
16	3	.01378701	.86638	8792.00
17	3	.01181000	.80224	9352.00
18	1	.01129178	.74178	9887.50
19	2	.01053106	.68407	10435.50
20	3	.01011648	.62741	10995.50
21	3	.00866581	.57809	11555.50
22	2	.00779399	.53617	12103.50
23	3	.00742316	.49860	12663.50
24	1	.00723049	.45589	13199.00
25	3	.00635870	.42028	13759.00
26	2	.00576630	.38867	14307.00
27	1	.00462991	.36387	14842.50
28	2	.00426909	.34048	15390.50
29	2	.00315954	.32316	15938.50
30	1	.00296468	.30729	16474.00
31	4	.00266460	.29250	17029.00
32	1	.00189638	.28233	17564.50
33	1	.00121559	.27583	18100.00
34	4	.00034748	.27390	18655.00
35	4	.00004531	.27364	19210.00
36	4	.00000591	.27361	19765.00
37	4	.00000077	.27361	20320.00
38	4	.00000010	.27361	20875.00
39	4	.00000001	.27361	21430.00
40	4	.00000000	.27361	21985.00

Table 8.14 EFFECT OF DISCOUNTING PAST DATA

Source	Pipe	Parameter	$k_n = k_\nu = 3$		$k_n = k_\nu = 1.5$	
			Updated mean	Updated st. dev	Updated mean	Updated st. dev
1	1	pH - Max	8.12	0.92	8.12	0.87
		pH - Min	8.12	1.14	8.12	1.08
		Lead	0.78	1.45	0.74	1.42
2	1	Chromium	0.218	0.246	0.200	0.221
		Copper	-0.711	0.502	-0.798	0.522
		Fluoride	24.6	3.61	24.5	3.68
3	1	BOD_5	1133	643	1138	651
		Phosphate	2.08	0.313	2.03	0.325
		Suspended Solids	3.29	0.274	3.30	0.259
4	1	Phosphate	0.490	0.925	0.490	0.925
		Suspended Solids	13.5	3.38	13.5	3.38
	2	Phosphate	3.78	2.72	3.78	2.72
		Suspended Solids	75.0	108	75.0	108

Compliance Data

The effect of compliance data (effluent data obtained by the monitoring agency) on the initial statistical descriptions of the source effluents is investigated in this subsection. Suppose that Source 2 is monitored twice in month 3. The compliance data for the two visits are given in Table 8.15. Comparison of these data with the self-monitoring data for Source 2, month 3 (Table 8.3b) shows that the compliance data for chromium and copper are near the monthly maximum self-monitoring value. For fluoride, one compliance value is near the maximum, the other is below the mean.

Table 8.15 COMPLIANCE DATA - SOURCE 2, MONTH 3

Parameter	Data Point No. 1, kg.	Data Point No.2, kg
Chromium	0.53	0.70
Copper	1.80	2.00
Fluoride	28.0	16.0

In the procedure that combines the self-monitoring and compliance monitoring data, there is a design parameter, γ, that specifies the relative confidence one has in the self-monitoring as compared to the compliance monitoring data. For example, a value of $\gamma = 2$ implies that one has twice as much confidence in the compliance monitoring data as in the self-monitoring data. In the examples that follow, γ will take on values 2 and 4.

Tables 8.16a and 8.16b show the effect of the compliance data on the initial statistical description; these tables are analogous to Table 8.4b. The row opposite month 3 is the estimated mean and standard deviation for month 3 without the compliance data. The row opposite 3* includes the compliance data. The tables show that the estimated mean and standard deviation for the month is substantially increased for chromium and copper. For fluoride, the mean is slightly decreased while the standard deviation is increased. The effect of the compliance data on the estimates is clearly much greater for $\gamma = 4$ than for $\gamma = 2$. By comparing the values of the updated mean and standard deviation at the end of month 4 in Tables 8.4b, 8.16a, and 8.16b,

Table 8.16a INITIAL STATISTICS FOR SOURCE 2 WITH COMPLIANCE MONITORING DATA: $\gamma = 2$

Month	Parameter: Chromium Distribution: Normal				Parameter: Copper Distribution: Lognormal				Parameter: Fluoride Distribution: Normal			
	Est. mean, kg	Est. st.dev., kg	Updated mean, kg	Updated st.dev., kg	Est. mean, log kg	Est. st.dev., log kg	Updated mean, log kg	Updated st.dev., log kg	Est. mean, kg	Est. st.dev., kg	Updated mean, kg	Updated st.dev., kg
1	0.216	0.321	---	---	-0.437	0.367	---		24.4	3.79	---	---
2	0.313	0.297	0.266	0.308	-0.685	0.474	-0.565	0.443	25.4	3.49	24.9	3.62
3	0.214	0.214	---	---	-0.570	0.337	---		24.7	3.29	---	---
3*	0.280	0.261	0.271	0.287	-0.437	0.471	-0.514	0.455	24.3	4.23	24.7	3.84
4	0.132	0.070	0.236	0.259	-1.146	0.404	-0.672	0.551	24.0	4.17	24.5	3.88

* Includes compliance monitoring data

Table 8.16b INITIAL STATISTICS FOR SOURCE 2 WITH COMPLIANCE MONITORING DATA: $\gamma = 4$

Month	Parameter: Chromium Distribution: Normal				Parameter: Copper Distribution: Lognormal				Parameter: Fluoride Distribution: Normal			
	Est. mean, kg	Est. st.dev., kg	Updated mean, kg	Updated st.dev., kg	Est. mean, log kg	Est. st.dev., log kg	Updated mean, log kg	Updated st.dev., log kg	Est. mean, kg	Est. st.dev., kg	Updated mean, kg	Updated st.dev., kg
1	0.216	0.321	---	---	-0.437	0.369	---	---	24.4	3.79	---	---
2	0.313	0.297	0.266	0.308	-0.685	0.474	-0.565	0.443	25.4	3.49	24.9	3.62
3	0.214	0.214	---	---	-0.570	0.337	---	---	24.7	3.29	---	---
3*	0.332	0.277	0.291	0.295	-0.333	0.515	-0.473	0.486	23.8	4.80	24.5	4.12
4	0.132	0.070	0.251	0.268	-1.146	-0.672	-0.642	0.583	24.0	4.17	24.4	4.07

* Includes compliance monitoring data

Table 8.17 EXPECTED DAMAGE AND PROBABILITY OF NO VIOLATION FOR SOURCE 2

Y	Parameter	Expected damage	Probability of no violation, %	Expected damage for source	Probability of no violation for source, %
NCD*	Chromium	0.08	82.6		
	Copper	0.12	96.1		
	Fluoride	0.00	93.1	0.12	74.0
2	Chromium	0.08	79.5		
	Copper	0.14	93.8		
	Fluoride	0.00	92.2	0.14	68.0
4	Chromium	0.08	77.1		
	Copper	0.17	92.0		
	Fluoride	0.00	91.7	0.17	65.0

* No compliance data

one can see the effect of the compliance monitoring data on the initial statistical description. Again, the effect is substantial. Table 8.17 compares the value of the expected damage and probability of no violation for source 2 for the three cases: no compliance data and compliance data for $\gamma = 2$ and $\gamma = 4$. The compliance data, for this case, have increased the expected damage and decreased the probability of no violation.

Upstream Concentration

The previous examples in this section have assumed that the concentration of each constituent, upstream from each source, has caused zero environmental damage. In this subsection, we will investigate the effect of changing the assumed upstream concentrations.

Five cases will be considered. Case I, for comparison purposes, corresponds to the zero upstream damage case described in Section VIII.2. For Cases II and III the upstream concentration is set to cause damage levels of 2 and 4 in the receiving waters (recall that "2" corresponds to "excellent" water quality and "4" corresponds to "acceptable" water quality). In Cases IV and V the upstream concentration is also set to cause damages of 2 and 4; however, in this case, the expected damage for each constituent that is calculated is the incremental damage, that is, the expected damage due to the source's constituent minus the damage in the receiving waters that exists if that constituent were not present in the effluent. For reference, the five cases are described in Table 8.18. Table 8.19 compares the expected damage for the five cases. The table shows how the damage increases as the assumed upstream concentration increases (Cases I, II and III). The incremental damage, however, actually decreases for most cases (Cases I, IV and V). This is because the damage functions are, for the most part, concave in shape. The one exception, in this example, is the fluoride in Source 2. The presence of fluoride in a stream does not cause any damage (it is actually beneficial) below a certain threshold. Above that threshold damage increases rapidly. Thus, for fluoride, the incremental damage is zero under zero upstream concentration; it increases greatly for an upstream concentration causing a damage of 2; and it decreases for an upstream concentration causing a damage of 4 (the damage curve is concave for large values of concentration).

The priority lists for the five cases are compared in Table 8.20. Comparing Cases II and III with Case I, it is seen that Sources 2 and 4 appear much higher on the list. Source 2 appears higher because of the above large increase in expected damage due to fluoride. Source 4 appears earlier because it now has an expected damage comparable with the other sources; its expected damage in Case I was much smaller than the expected damage for Sources 1 and 3. Comparing Cases IV and V with the other cases, it is seen that Source 1 has lower sampling priority. Source 4 also appears lower on the lists. These phenomena both reflect the lower expected incremental damage of Sources 1 and 4 as compared to Sources 2 and 3.

Table 8.20 shows the large sensitivity of the priorities to changes in assumed upstream concentration. It is preferable to use the incremental expected damage over the "regular" expected damage since one is basically interested in the damage caused by a source and not just by the expected damage in the river (which will also depend on the upstream concentration). The value of assumed upstream concentration used should reflect the average condition of the stream in a region containing the source.

Table 8.18 CASES CONSIDERED FOR SENSITIVITY STUDY OF UPSTREAM CONCENTRATION

Case	Assumed upstream level of damage	Incremental damage
I	0	---
II	2	No
III	4	No
IV	2	Yes
V	4	Yes

Table 8.19 COMPARISON OF EXPECTED DAMAGE FOR VARIOUS ASSUMED UPSTREAM CONCENTRATIONS

Source	**Constituent**	**Expected Damage**				
		Case I	**Case II**	**Case III**	**Case IV**	**Case V**
1	pH	0.29	2.13	4.02	0.14	0.05
	Lead	1.60	2.45	4.40	0.47	0.42
2	Chromium	0.08	2.05	4.00	0.05	0.01
	Copper	0.12	2.03	4.00	0.03	0.01
	Fluoride	0.00	3.49	4.49	1.53	0.54
3	BOD_5	3.22	4.29	5.20	2.63	1.83
	Phosphates	3.64	4.59	5.19	2.93	1.88
	Suspended Solids	0.37	2.03	3.67	0.37	0.36
4	Phosphates	0.29	2.28	4.09	0.29	0.10
	Suspended Solids	0.03	2.02	4.00	0.03	0.02

Table 8.20 PRIORITY LISTS, VARIOUS ASSUMED UPSTREAM CONCENTRATIONS

Priority	Source Sampled				
	Case I	Case II	Case III	Case IV	Case V
1	1	4	4	3	3
2	3	2	1	2	3
3	3	1	2	3	3
4	1	2	1	3	3
5	3	3	2	2	1
6	3	1	3	3	3
7	3	3	1	4	2
8	4	2	2	3	3
9	1	3	3	2	2
10	3	3	3	3	3
11	3	1	2	1	1
12	3	2	3	3	4
13	1	3	4	2	3
14	3	3	1	3	2
15	3	2	3	2	3
16	1	4	2	3	3
17	1	3	3	1	1
18	1	1	3	3	2
19	4	3	1	2	2
20	2	2	2	1	1
21	1	3	3	2	2
22	2	3	3	2	1
23	2	1	2	1	2
24	1	2	3	2	2
25	2	2	1	4	1

SECTION IX

DEMONSTRATION PROJECT

The priority procedure will be demonstrated, in this section, using data supplied by the State of Michigan, Department of Natural Resources. The data, taken over a two year period, is from 30 industries and municipal treatment plants. Table 9.1 gives a brief description of the various sources. As can be seen, a variety of pollutants and types of plants have been included.

The purpose of the demonstration project is two-fold. First, it will demonstrate the procedure on the types of data bases that will be available to the monitoring agencies. Second, it will compare the performance of the procedure with another, simpler, priority setting procedure.

IX.1 DESCRIPTION OF DATA AND ASSUMPTIONS

The quality of the data varied greatly from source to source. For several sources, there were twenty four months of data; for others, there was as little as six. Some sources sampled their effluent daily, others weekly, and others monthly. Standards were not set for approximatley 20% of the constituents reported. In order to test the priority procedure with as many constituents as possible, reasonable hypothetical standards were established for these constituents. Also, most of the standards were on the concentration of the constituent in the effluent. Since, in the future, standards will typically be on the mass loading, it was decided to transform the given standards into mass loading standards by multiplying them by the daily effluent flow of the source, given on the permits.

The value of the upstream flow of the receiving waters was taken to be the seven-day, ten-year low flow. This value will give a much smaller flow than would be encountered in a typical month (it was used because

Table 9.1 DESCRIPTION OF EFFLUENT SOURCES

Source number	Pipe Number	Avg. daily flow, MGD	Type of plant	Type of waste, %*			Constituents
				Proc	Cool	San	
1	1	0.07	Chem	100	---	---	pH, chromium, nickel, chloroform extract
	2	0.0035		---	2	98	BOD, suspended solids, chloride
2	1	0.106	Porcelain man.	90	10	---	Phosphorus, pH, suspended solids, chloroform extract
	2	0.124		25	75	---	Phosphorus, pH, suspended solids, chloroform extract
3	1	0.085	Porcelain man.	40	40	20	pH, suspended solids, phosphorus
4	1	0.2	Auto parts	1	99	---	pH, suspended solids, chloroform extract
	2	0.08		---	100	---	pH, suspended solids, chloroform extract
5	1	720.	Power	1	98	1	pH, chloride
6	1	4.436	Chem	1	99	---	pH, oil-grease, phenol, COD
	2	8.07		1	99	---	pH, oil-grease, phenol, COD
7	1	0.75	Chem	46	54	---	pH, suspended solids, phosphorus, fluoride, copper, lead
8	1	0.14	Chem	70	30	---	pH, suspended solids, phosphorus, cyanide, fluoride, chromium, copper, lead, chloroform extract

* "Proc", "Cool" and "San" denote processing, cooling and sanitary waste, respectively.

Table 9.1 DESCRIPTION OF EFFLUENT SOURCES (Cont'd)

Source number	Pipe number	Avg. daily flow, MGD	Type of plant	Type of waste, %*			Constituents
				Proc	Cool	San	
9	1	5.	Auto	40	60	---	BOD, pH, suspended solids, chromium, nickel, chloroform extract
10	1	0.35	Auto	100	---	---	pH, suspended solids, phosphorus, chloroform extract, oil-grease
11	1	0.69	Auto body	100	---	---	pH, cyanide, chromium, copper, nickel
12	1	1.1	Auto	24	76	---	BOD, pH, suspended solids, chloroform extract
13	1	0.129	Auto parts	14	86	---	BOD, pH
14	1	0.38	Auto	57	43	---	pH, suspended solids, cyanide, chromium, copper, chloroform extract
15	1	0.223		100	---	---	pH, lead
16	1	0.184	Electronics	20	80	---	pH, suspended solids, oil-grease, mercury
17	1	0.53	Metal	---	100	---	Chloroform extract
	2	0.123		---	100	---	Chloroform extract
	3	0.137		---	100	---	Chloroform extract
	4	0.828		100	---	---	pH, suspended solids, phosphorus, aluminum, chloroform extract

* "Proc", "Cool" and "San" denote processing, cooling and sanitary waste, respectively.

Table 9.1 DESCRIPTION OF EFFLUENT SOURCES (Cont'd)

Source number	Pipe number	Avg. daily flow, MGD	Type of plant	Type of waste, %*			Constituents
				Proc	Cool	San	
18	1	10.	Chem				BOD, suspended solids, ammonia, dissolved solids
19	1	1.3	Glass	---	100	---	Suspended solids, chloroform extract
20	1	0.527	Refrig. man.	86	14	---	pH, suspended solids, phosphorus
21	1	Unknown	Power	---	100	---	pH, chloride
	2			---	100	---	BOD
	3			---	100	---	Suspended solids
	4			---	100	---	Suspended solids, BOD
22	1	10.	STP†	---	---	100	DO, BOD, suspended solids, phosphorus
23	1	0.114	STP	---	---	100	BOD, suspended solids, phosphorus
24	1	0.718	STP	---	---	100	BOD, suspended solids
25	1	43.6	STP	---	---	100	BOD, suspended solids
26	1	1.91	STP	---	---	100	DO, BOD, suspended solids, phosphorus
27	1	1.54	STP	---	---	100	BOD, suspended solids, phosphorus

* "Proc", "Cool" and "San" denote processing, cooling and sanitary waste, respectively.

† Sewage treatment plant.

Table 9.1 DESCRIPTION OF EFFLUENT SOURCES (Cont'd)

Source number	Pipe number	Avg. daily flow, MGD	Type of plant	Type of waste, %*			Constituents
				Proc	Cool	San	
28	1	28.0	STP†	---	---	100	DO, BOD, suspended solids, phosphorus
29	1	0.960	STP	---	---	100	BOD, suspended solids
30	1	9.3	STP	---	---	100	BOD, suspended solids

* "Proc", "Cool" and "San" denote processing, cooling and sanitary waste, respectively.

† Sewage treatment plant.

it was readily available). In order to obtain better estimates of the environmental damage that is likely to occur, it is suggested that one use the minimum average monthly flow where the minimum is taken over the months in the monitoring period.

The distributions used for the various constituents were obtained as follows: The mean and standard deviation were first estimated for all constituents under the normal distribution assumption. For those constituents whose standard deviation was greater than the mean, it was inferred that the normal distribution did not give a good fit to the data. The distribution assumption for these constituents was changed to lognormal. This method of assigning distributions is based on the following considerations. Under the normal assumption,there is a finite probability of having a negative discharge. Since this is almost always impossible, this probability is interpreted as being the probability of having a zero discharge (i.e. the normal density function is changed so that all the area to the left of zero is put at zero). Thus, the above method of assigning distributions, though somewhat arbitrary, is based on the fact that if, under the normal distribution assumption, the standard deviation is greater than the mean, then there is a large probability that the source will not produce that constituent. Since, typically, the constituent will be produced, a lognormal distribution is judged more appropriate.

Other assumptions made were:

(1) The BOD-DO transfer coefficient, K_{BOD-DO}, was assumed to be 0.5 for all sources.*

(2) The saturation level of DO, DOSAT, was assumed to be 9 mg/l for all sources.*

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* K_{BOD-DO} and DOSAT are defined in Section VI.1

(3) The concentration of dissolved oxygen in an effluent was assumed to be 0 mg/l in the sources for which there was a standard for BOD and which did not report their DO discharge.

(4) The design parameters k_n and k_ν, which determine the degree of discounting of past data, were set to 3. *

(5) The constituents of a source are assumed uncorrelated.

(6) The concentration of the pollutants upstream from the source (CU) were assumed to be at a level to cause zero damage.

Table 9.2 lists the assumed monetary resources required to sample the sources. The amounts are a function of two quantities: the number of outfalls of the source and the number and types of pollutants sampled. The exact method used to determine the resources is given in Appendix D.

---

* k_n and k_ν are defined in Section V.2.

Table 9.2 RESOURCES REQUIRED TO MONITOR THE SOURCES

Source	Required Resources
1	$ 588.00
2	591.00
3	543.00
4	571.00
6	576.00
7	566.00
8	603.50
9	583.00
10	568.00
11	565.50
12	568.00
13	548.00
14	578.00
15	535.00
16	558.00
17	943.50
18	565.00
19	545.00
20	543.00
22	563.00
23	560.00
24	550.00
25	550.00
26	563.00
27	560.00
28	563.00
29	550.00
30	550.00

IX.2 PERFORMANCE OF PROCEDURE

In this subsection the Resource Allocation Program is used to obtain sampling frequencies based on the demonstration case data. Three examples are considered. For each of the examples, the monitoring period (i.e., the time period for which the allocation is based) is assumed to be six months. The examples are:

Case I. Use the first twelve months of data to obtain the initial source statistical descriptions. Determine the sampling frequencies for the following monitoring period (i.e., months 13 through 18).

Case II. Use the data from months 13 through 18 to update the statistical description of the sources used in Case I. Determine the sampling frequencies for the following monitoring period (i.e., months 19 through 24).

Case III. Obtain a revision of the sampling frequencies obtained in Case II, under the assumption that the sampling has to be interrupted in the middle of a sampling period due to a measurement of very poor water quality in a given river segment. (It is desired to sample two sources, which are expected to cause the poor quality, twice in the remainder of the monitoring period.)

This subsection is concluded with a comparison of the performance of the priority procedure developed in this report with a procedure that assigns sampling frequency on the basis of source flow.

Case I

The source expected damage and probability of no violation obtained from the first 12 months of self-monitoring data is given in Table 9.3.* The statistical description of the sources' constituents, and the

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* Sources 5 and 21 are not included in this example due to insufficient data.

Table 9.3 DATA FOR CASE 1

SOURCE	PNV*	EXP. DAMAGE
1	.640361	1.824476
2	.366900	1.355373
3	.971105	.000615
4	.434765	3.428362
6	.966816	4.047932
7	.111617	3.517227
8	.006504	1.408283
9	.089683	7.781987
10	.072174	4.489711
11	.814871	2.719460
12	.138667	5.660459
13	.921435	3.340151
14	.964880	2.432983
15	.000060	2.813442
16	.981822	4.072095
17	.316116	4.018275
18	.034052	8.942007
19	.809288	5.787722
20	.696925	.388792
22	.117219	5.959835
23	.716378	4.220618
24	.992393	1.098906
25	.050330	3.746962
26	.388621	.601895
27	.000000	6.574204
28	.663566	6.318164
29	.883175	6.091859
30	.258403	1.090917

---

* Probability of no violation.

expected damage and probability of no violation for each constituent used to obtain the information in Table 9.3, is given in full in Appendix G.1.

In this example, the upper and lower bounds on the sampling frequencies are 0 and 3 respectively and the monitoring agency's budget is $25,000. Table 9.4 gives the resulting priority list and Table 9.5 gives the sampling frequencies. Comparing these tables with Table 9.3, it is seen that those sources sampled most often and/or with highest priority have high expected damage and low probability of no violation.

Case II

The assumptions and constraints for Case II are identical with those for Case I. The new expected damage and probability of violation for each source, based on the updated statistics is given in Table 9.6. The large effect of the update procedure on this data can be determined by comparing this table with Table 9.3. For example, the probability of no violation for source 20 went from 69.7% for Case I to 33.3% for Case II while the expected damage went from 0.387 to 0.737. The updated statistical description, the expected damage and the probability of no violation, for each constituent, is given in Appendix G.2.

Table 9.7 gives the priority list for this example, and Table 9.8 gives the sampling frequencies. There are large differences in some of the sampling frequencies for Cases I and II. For example, Source 6 was not sampled in Case I (Table 9.5) but was sampled two times in Case II (Table 9.8). Conversely, Source 11 was sampled three times in Case I but was not sampled in Case II. These changes are due to changes in the expected damage and probability of no violation for the sources.

Table 9.4 PRIORITY LIST: DEMONSTRATION PROJECT, CASE I

PRIORITY	SOURCE SAMPLED	MARGINAL RETURN X100	COST OF UNDETECTED VIOLATIONS	RESOURCES REQUIRED
1	18	1.52876276	95.09519	565.00
2	9	1.21510726	88.01112	1148.00
3	27	1.17396499	81.43692	1708.00
4	22	.93449891	76.17569	2271.00
5	12	.85837021	71.30014	2839.00
6	10	.73339251	67.13447	3407.00
7	25	.64697755	63.57610	3957.00
8	7	.55205745	60.45145	4523.00
9	15	.52535465	57.63818	5058.50
10	28	.37755728	55.51253	5621.50
11	4	.33937480	53.57470	6192.50
12	17	.29125971	50.82667	7136.00
13	28	.25053405	49.41616	7699.00
14	8	.23183490	48.01704	8302.50
15	23	.21376098	46.81998	8862.50
16	19	.20252984	45.71619	9407.50
17	28	.16624579	44.78023	9970.50
18	19	.16390498	43.88694	10515.50
19	23	.15313359	43.02940	11075.50
20	4	.14754831	42.18690	11646.50
21	30	.14709458	41.37788	12196.50
22	2	.14519234	40.51979	12787.50
23	19	.13264635	39.79687	13332.50
24	29	.12939626	39.06519	13882.50
25	12	.11902722	38.40911	14450.50
26	29	.11427958	37.78058	15000.50
27	1	.11159047	37.12442	15588.50
28	23	.10970148	36.51010	16148.50
29	22	.10954107	35.89338	16711.50
30	9	.10897437	35.25806	17294.50
31	29	.10092891	34.70295	17844.50
32	17	.09207177	33.83425	18788.00
33	11	.08902778	33.33080	19353.50
34	11	.07254612	32.92055	19919.00
35	1	.07145823	32.50038	20507.00
36	26	.06536158	32.13240	21070.00
37	4	.06414885	31.76611	21641.00
38	7	.06161888	31.41734	22207.00
39	11	.05911570	31.08304	22772.50
40	2	.05327107	30.76821	23363.50
41	10	.05293204	30.46756	23931.50
42	18	.05205818	30.17343	24496.50
43	13	.04788692	29.91101	25044.50
44	1	.04575910	29.64195	25632.50
45	13	.04412466	29.40014	26180.50
46	13	.04065799	29.17734	26728.50
47	30	.03800971	28.96828	27278.50
48	25	.03256254	28.78919	27828.50
49	17	.02910533	28.51458	28772.00

Table 9.5 SAMPLING FREQUENCIES: DEMONSTRATION PROJECT, CASE I

```
                        BUDGET  25000.00

         MIN NO.    MAX NO.                                  COST OF
         SAMPLES    SAMPLES    TIMES      RESOURCES   UNDETECTED
SOURCE   REQUIRED   ALLOWED    SAMPLED       USED       VIOLATIONS
-----------------------------------------------------------------


   1           0         3          2      1176.00        .74815
   2           0         3          2      1182.00        .18245
   3           0         3          0          .00        .00061
   4           0         3          3      1713.00        .28174
   6           0         3          0          .00       4.04793
   7           0         3          2      1132.00        .04382
   8           0         3          1       603.50        .00916
   9           0         3          2      1166.00        .06259
  10           0         3          2      1136.00        .02339
  11           0         3          3      1696.50       1.47146
  12           0         3          2      1136.00        .10884
  13           0         3          0          .00       3.34015
  14           0         3          0          .00       2.43298
  15           0         3          1       535.50        .00017
  16           0         3          0          .00       4.07209
  17           0         3          2      1887.00        .40154
  18           0         3          2      1130.00        .01037
  19           0         3          3      1635.00       3.06773
  20           0         3          0          .00        .38879
  22           0         3          2      1126.00        .08189
  23           0         3          3      1680.00       1.55168
  24           0         3          0          .00       1.09891
  25           0         3          1       550.00        .18859
  26           0         3          1       563.00        .23391
  27           0         3          1       560.00        .00000
  28           0         3          3      1689.00       1.84605
  29           0         3          3      1650.00       4.19653
  30           0         3          1       550.00        .28190

-----------------------------------------------------------------

TOTAL RESOURCES USED 24496.50
FINAL COST OF UNDETECTED VIOLATIONS  30.17343
```

Table 9.6 DATA FOR CASE II

SOURCE	PNV*	EXP. DAMAGE
1	.696278	2.747735
2	.147692	1.701061
3	.979586	.000607
4	.531608	3.106736
6	.308329	3.762632
7	.111616	3.517227
8	.000191	1.513851
9	.032648	8.724413
10	.075379	5.623020
11	.938505	2.099448
12	.172521	5.397685
13	.743805	3.535545
14	.991440	2.267273
15	.000857	2.375780
16	.994912	4.120321
17	.316189	3.986394
18	.021793	9.106810
19	.974799	3.822610
20	.333279	.736836
22	.232609	5.389093
23	.394030	4.628968
24	.922821	.923437
25	.107414	3.571862
26	.484105	.475020
27	.000000	6.675322
28	.615132	6.203027
29	.792984	6.596327
30	.163917	1.191331

---

* Probability of no violation.

Table 9.7 PRIORITY LIST: DEMONSTRATION PROJECT, CASE II

PRIORITY	SOURCE SAMPLED	MARGINAL RETURN X100	COST OF UNDETECTED VIOLATIONS	RESOURCES REQUIRED
1	18	1.57669804	94.89202	565.00
2	9	1.44761255	86.45244	1148.00
3	27	1.19202173	79.77712	1708.00
4	10	.91534568	74.57796	2276.00
5	12	.78635087	70.11149	2844.00
6	22	.73455494	65.97595	3407.00
7	25	.57967182	62.78775	3957.00
8	7	.55205768	59.66311	4523.00
9	23	.50089564	56.85869	5083.00
10	6	.45162335	54.25559	5659.00
11	15	.44327629	51.66184	6194.50
12	28	.42404060	49.49449	6757.50
13	17	.28891804	46.76855	7701.00
14	28	.26084082	45.30002	8264.00
15	4	.25484597	43.84465	8835.00
16	8	.25079741	42.33129	9438.50
17	29	.24828064	40.96574	9988.50
18	2	.24531773	39.51541	10579.50
19	23	.19736782	38.41066	11139.50
20	29	.19688254	37.32780	11689.50
21	30	.18110030	36.33175	12239.50
22	22	.17083395	35.36979	12802.50
23	13	.16528967	34.46460	13350.50
24	28	.16045145	33.56066	13913.50
25	29	.15612484	32.70197	14463.50
26	1	.14192987	31.86742	15051.50
27	6	.13931040	31.06500	15627.50
28	12	.13566206	30.29444	16195.50
29	4	.13547814	29.52066	16766.50
30	13	.12294336	28.84713	17314.50
31	1	.09882264	28.26605	17902.50
32	13	.09144594	27.76493	18450.50
33	17	.09135259	26.90301	19394.00
34	20	.09047219	26.41175	19937.00
35	23	.07776874	25.97625	20497.00
36	4	.07202126	25.56500	21068.00
37	10	.06899758	25.17310	21636.00
38	1	.06280803	24.76851	22224.00
39	25	.06226493	24.42605	22774.00
40	7	.06161870	24.07729	23340.00
41	9	.04726118	23.80176	23923.00
42	26	.04352768	23.55669	24486.00
43	6	.04295348	23.30928	25062.00
44	22	.03974448	23.08552	25625.00
45	2	.03623144	22.87139	26216.00
46	18	.03435129	22.67725	26781.00
47	20	.03015250	22.51352	27324.00
48	30	.02968543	22.35026	27874.00
49	17	.02888465	22.07773	28817.50

Table 9.8 SAMPLING FREQUENCIES: DEMONSTRATION PROJECT, CASE II

```
                        BUDGET  25000.00

         MIN NO.    MAX NO.                            COST OF
         SAMPLES    SAMPLES     TIMES     RESOURCES  UNDETECTED
SOURCE  REQUIRED    ALLOWED    SAMPLED       USED    VIOLATIONS
---------------------------------------------------------------


   1            0         3          3     1764.00       .92752
   2            0         3          1      591.00       .25123
   3            0         3          0         .00       .00061
   4            0         3          3     1713.00       .46674
   6            0         3          2     1152.00       .35770
   7            0         3          2     1132.00       .04382
   8            0         3          1      603.50       .00029
   9            0         3          2     1166.00       .00930
  10            0         3          2     1136.00       .03195
  11            0         3          0         .00      2.09945
  12            0         3          2     1136.00       .16065
  13            0         3          3     1644.00      1.45490
  14            0         3          0         .00      2.26727
  15            0         3          1      535.50       .00204
  16            0         3          0         .00      4.12032
  17            0         3          2     1887.00       .39854
  18            0         3          1      565.00       .19847
  19            0         3          0         .00      3.82261
  20            0         3          1      543.00       .24557
  22            0         3          2     1126.00       .29159
  23            0         3          3     1680.00       .28319
  24            0         3          0         .00       .92344
  25            0         3          2     1100.00       .04121
  26            0         3          1      563.00       .22996
  27            0         3          1      560.00       .00000
  28            0         3          3     1689.00      1.44380
  29            0         3          3     1650.00      3.28924
  30            0         3          1      550.00       .19528

---------------------------------------------------------------

TOTAL RESOURCES USED 24486.00
FINAL COST OF UNDETECTED VIOLATIONS  23.55669
```

Case III

For Case III, it is assumed that sampling from Case II has been interrupted in the middle of a monitoring period. It is expected that Source 14 or Source 19 is contributing to poor water quality. From Table 9.8, it is seen that neither of these sources would normally be sampled during this monitoring period.

Table 9.9 shows the number of times the sources were assumed sampled before the interrupt and the optimal sampling frequencies after the interrupt. Case III has shown how the priority procedure can be used to respond to ambient monitoring reports.

Preliminary Performance Comparison

The performance of the Resource Allocation Program will be compared with a simpler procedure that assigns sampling frequencies on the basis of flow. The latter procedure, called the Allocation by Flow procedure, assigns one sample to all the sources and then assigns the remaining samples, within the budget, to the sources with largest flow.

The monitoring period used for this comparison will be the one corresponding to Case II, (i.e., months 19 through 24) where the sampling frequencies were based on data from months 1 through 18.

The performance criteria are (i) the observed "cost" of undetected violations and (ii) the observed number of violators. These criteria are observed values calculated for 14 sources for a month picked at random from the monitoring period.*

---

*The number of sources considered for this comparison were reduced to 14 to reduce the amount of data handling required.

Table 9.9 SAMPLING FREQUENCIES BEFORE AND AFTER INTERRUPT: DEMONSTRATION PROJECT, CASE III

Source	Times sampled before interrupt	Times sampled after interrupt
1	2	0
2	1	0
3	0	0
4	1	1
6	1	0
7	2	0
8	0	1
9	0	2
10	1	0
11	0	1
12	1	1
13	2	0
14	0	2
15	0	1
16	0	0
17	0	2
18	0	1
19	0	3
20	1	0
22	1	1
23	2	1
24	0	0
25	0	1
26	1	0
27	0	1
28	1	2
29	2	1
30	1	0

The observed "cost" of undetected violations for one month is

$$\bar{c} = \sum_{\text{sources}} \bar{c}_i \, \bar{p}_i^{\,s_i} \qquad (9.1)$$

where

$\bar{c}_i$ = average damage due to source i

$= \frac{1}{M} \sum_{k=1}^{M}$ (observed damage on day k)

$1-\bar{p}_i$ = observed frequency of violation of source i

= (number of days in violation) ÷ M

s_i = sampling frequency for source i.

and where M is the number of observed values of the effluent in the month. The observed damage on day k is

$$\max_{\substack{\text{constituents}\\ j}} \{d_j(\overline{CO}_{ij}(k))\} \qquad (9.2)$$

where d_j is the damage function for constituent j and $\overline{CO}_{ij}(k)$ is the concentration of constituent j downstream from source i based on the observed effluent value for constituent j on day k. (Note that the assumed upstream concentration and stream parameters are the same as were used in the priority procedure to determine the sampling frequencies.) The observed number of violators in a month is simply

$$\bar{V} = \sum_{\text{Sources}} (1 - \bar{p}_i^{\,s_i}) \qquad (9.3)$$

Table 9.10 shows the observed frequency of violation, $1-\bar{p}_i$, and the average damage, $\bar{C}_i$, for the various sources along with the source flow. These values were used to calculate the observed "cost" of undetected violations and observed number of violators. Table 9.11 compares the sampling frequencies obtained by the Allocation by Flow method and the Resource Allocation Program (two lower bounds on sampling frequency were chosen for the Resource Allocation Program: zero and one.) as well as comparing the performance criteria. The budget was assumed to be $15,000. From Table 9.11 it is seen that the Resource Allocation Program produces a better allocation for this example than the Allocation by flow method. The improvement is greater for the observed "cost" of undetected violations than for the observed number of violators.

It is recommended that more comparison studies be done in the future using larger data bases. This study was hampered by the fact that only one month of data was used. Since samples are highly correlated, day-to-day, for many industries, a small number of independent samples went into the calculation of the observed damage and the observed frequency of violation. (Note that over half the sources were either always in violation or never in violation.) It therefore is expected that much better performance of the Resource Allocation Program would have been shown if more months of data were used in the comparison.

Table 9.10 OBSERVED FREQUENCY OF VIOLATION AND AVERAGE DAMAGE

Source	Source flow, Ml/day	Observed frequency of violation, %	Observed average damage
3	0.075	0.0	0.00
12	4.92	41.4	5.73
16	0.725	22.2	3.01
18	35.55	50.0	3.90
19	0.133	0.0	1.32
22	40.75	100.0	6.85
23	0.425	13.3	4.01
24	3.04	0.0	0.98
25	165.0	100.0	3.70
26	7.15	100.0	0.43
27	5.57	100.0	2.61
28	110.9	100.0	4.15
29	4.11	5.0	5.79
30	35.0	87.1	1.13

Table 9.11 PERFORMANCE COMPARISON

Source	Sampling Frequencies		
	Allocation By	Optimal Allocation $s_i \geq 1$	Optimal Allocation $s_i \geq 0$
3	1	1	0
12	1	2	2
16	1	1	0
18	2	1	2
19	1	1	0
22	2	2	3
23	1	2	3
24	1	1	0
25	2	1	2
26	2	1	1
27	2	1	1
28	2	3	3
29	1	3	3
30	2	1	1
Observed "cost" of undetected violations	19.00	17.97	17.23
Observed number of violators caught	7.55	7.64	7.77

SECTION X

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SECTION XI

GLOSSARY

TERMINOLOGY

BOD - Biochemical oxygen demand.

COD - Chemical oxygen demand.

DO - Dissolved oxygen.

K_{BOD-DO} - BOD-dissolved oxygen transfer coefficient

Damage - A measure of effect of pollutants on water quality.

Effluent Standard - A restriction on the quantities or concentrations of constituents from an effluent source.

Monitor - The government agency having responsibility for enforcing laws realting to the abatement of pollution.

Permit - A document or requirement regulating the discharge of pollutants.

Resources - Money required to obtain and process effluent samples obtained during compliance monitoring.

Resource Allocation Program - Name given to procedure for setting compliance monitoring priorities.

Source - A discharger or possible discharger of pollutants subject to effluent standards.

Water Quality Limited Segment - A segment of a river where it is known that water quality does not meet applicable water quality standards and which is not expected to meet water quality standards even after the application of the effluent limitations required by the Water Pollution Control Act.

MATHEMATICAL NOTATION

A - Maximum allowed cost of undetected violations.

α - Level of significance of a statistical hypothesis test.

B - Monitoring agency's budget.

SECTION XI

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MATHEMATICAL NOTATION

A - Maximum allowed cost of undetected violations.

α - Level of significance of a statistical hypothesis test.

B - Monitoring agency's budget.

C - Total "cost" of undetected violations.

$C_i(S_i)$ - "Cost" of undetected violations for source i.

c_i - Expected damage from all the constitutents of source i.

CO_{ij} - Stream concentration at discharge point, constituent j, source i.

CU_{ij} - Upstream concentration, constituent j, source i.

CX_{ij} - Downstream concentration, constituent j, source i.

D_{ij} - Expected damage due to constituent j, source i.

$D_{ij\ell}$ - Expected damage due to constituent j, from source i into stream ℓ.

$d_j(\cdot)$ - Damage function for constituent j.

$D_{i,BOD}$ - Dissolved oxygen deficit due to BOD, source i.

$D_{i,COD}$ - Dissolved oxygen deficit due to COD, source i.

$DOMIN_{i,BOD}$ - Minimum DO level downstream from source i.

$\phi_{ij}(\cdot)$ - Density function of mass loading M_{ij}.

γ - Parameter denoting relative weight given compliance data over self-monitoring data.

h_n - Factor relating confidence in mean to number of measurements.

h_ν - Factor relating confidence in variance to the number of measurements.

i - Index denoting source.

j - Index denoting constituent.

k - Index denoting outfall.

ℓ - Index denoting receiving water.

k_n - Constant for determining the confidence in mean.

k_ν - Constant for determining the confidence in variance.

ℓ_i - Lower bound on sampling frequency for source i.

L_i - Upper bound on the sampling frequency for source i.

M_{ij} - Effluent mass loading, constituent j. source i.

mg/l - Milligrams per liter.

Ml - Megaliters.

m - Estimate of mean

μ - Mean of a random process.

$\hat{\mu}$ - Estimate of mean, μ.

$\mu_i(\cdot)$ - Marginal return function.

N - Number of sampling days in monitoring period.

n - Number of measurements or confidence in mean estimate.

n_s - Number of sources.

$p(\cdot)$ - Probability event occurs.

P_i - Probability of no violation for all constituents of source i.

P_{ij} - Probability of no violation for constituent j, source i.

P_{ijk} - Probability of no violation due to constituent j, outfall k, source i.

QS_i - Effluent flow rate, source i.

QU_i - Upstream flow rate, source i.

QX_i - Downstream flow rate, source i.

$R(\cdot)$ - Resources required to monitor all the sources.

r_i - Resources required to monitor source i once.

s_i - Number of times the ith source is sampled in monitoring period.

σ - Standard deviation of a random process.

$\hat{\sigma}$ - Estimate of standard deviation, σ.

τ_{ij} - Standard for constituent j, source i.

v - Estimate of variance.

V_i - Event ith source is in violation.

$\overline{V}_i$ - Event ith source is not in violation.

ν - Confidence in variance estimate.

x - Distance downstream from source or a random process.

y - Maximum of a set of data.

z_i - Compliance monitoring data.

APPENDIX A

ESTIMATION OF DISTRIBUTION PARAMETERS

In this Appendix the estimation of the parameters of the normal and log-normal probability density functions is discussed for the case where the available data consist of the sample mean and maximum of a set of observations. These two problems are treated in Sections A.1 and A.2. Section A.3 deals with the examination of the parameters when the available data consist of the maximum and the minimum value of a set of observations.

A.1 THE NORMAL CASE

In this case the process x is assumed normally distributed with mean μ and variance σ^2. The available data to estimate μ and σ is

$$z = [m,\xi] \tag{A.1.1}$$

where m is the sample mean and

$$\xi = \max \{x_1,\ldots,x_n\} . \tag{A.1.2}$$

Approximate maximum likelihood estimates of μ and σ^2 will now be obtained.

The calculation of the likelihood function

$$p(m,\xi|\mu,\sigma^2) \tag{A.1.3}$$

requires the joint probability density function for m and ξ. This density is not obtainable in closed form. Approximate maximum likelihood estimates can be obtained by estimating μ by m, the sample mean. $\hat{\sigma}$, the estimate of σ, is then that value of σ that maximizes

$$p(\xi|\mu = m,\sigma^2) \tag{A.1.4}$$

The above density is obtained as follows:

$$\text{Prob}\ \{\max(x_1, \ldots, x_n) \leq \xi | \mu, \sigma\} = F^n \left(\frac{\xi-\mu}{\sigma}\right) \tag{A.1.5}$$

where

$$F(\alpha) \triangleq \int_{-\infty}^{\alpha} (2\pi)^{-1/2} e^{-x^2/2}\, dx \tag{A.1.6}$$

Therefore,

$$p(\xi|\mu,\sigma) = \frac{d}{d\xi} F^n \left(\frac{\xi-\mu}{\sigma}\right) \tag{A.1.7}$$

For convenience denote

$$x_i' \triangleq x_i - \mu \tag{A.1.8}$$

then

$$\xi' = \max\{x_i', \ldots, x_n'\} = \xi - \mu \tag{A.1.9}$$

and, hence

$$p(\xi'|\sigma) = \frac{\partial}{\partial \xi'} F^n\left(\frac{\xi'}{\sigma}\right) \tag{A.1.10}$$

Let

$$f(y) = \frac{d}{dy} F(y) = \frac{1}{\sqrt{2\pi}} e^{-y^2/2} \tag{A.1.11}$$

Denoting

$$\zeta \triangleq \frac{\xi'}{\sigma} = \frac{\xi-\mu}{\sigma} \tag{A.1.12}$$

(A.1.10) becomes

$$p(\xi'|\sigma) = nF^{n-1}(\zeta)\, f(\zeta)\, \frac{1}{\sigma} \tag{A.1.13}$$

$$= nF^{n-1}(\zeta) \quad f(\zeta)\,\frac{\zeta}{\xi}$$

The likelihood equation is therefore

$$\frac{\partial}{\partial\sigma}\,p(\xi'|\sigma) = \frac{\partial p}{\partial\zeta}\,\frac{\partial\zeta}{\partial\sigma} - \frac{\partial p}{\partial\zeta}\,\frac{\xi'}{\sigma^2} = 0 \qquad \text{(A.1.14)}$$

which is equivalent to

$$\frac{\partial p}{\partial\zeta} = 0 \qquad \text{(A.1.15)}$$

Note that

$$\frac{df(\zeta)}{d\zeta} = \zeta f(\zeta) \qquad \text{(A.1.16)}$$

Thus (A.1.15) can be written as follows

$$(n-1)F^{n-2}(\zeta)\ f^2(\zeta)\zeta - F^{n-1}(\zeta)f(\zeta)\zeta^2 + F^{n-1}(\zeta)f(\zeta) = 0 \qquad \text{(A.1.17)}$$

or

$$\frac{(\zeta^2-1)F(\zeta)}{\zeta f(\zeta)} = n-1 \qquad \text{(A.1.18)}$$

The left hand side of (A.1.18) is plotted in Figure A.1.1. Using this figure, it is easy to determine $\hat{\sigma}$, the estimate of σ, given ξ, μ and n. This is done by obtaining $\hat{\zeta}$ for the given n from Figure A.1.1, then

$$\hat{\sigma} = \frac{\xi-\mu}{\zeta} \qquad \text{(A.1.19)}$$

For example, suppose $n = 31$, $\mu = 5$ and $\xi = 10$. From the figure, $(n-1) = 30$ implies $\zeta \approx 2.035$. Thus

$$\hat{\sigma} = \frac{\xi-\mu}{2.035} = \frac{5}{2.035} \approx 2.46$$

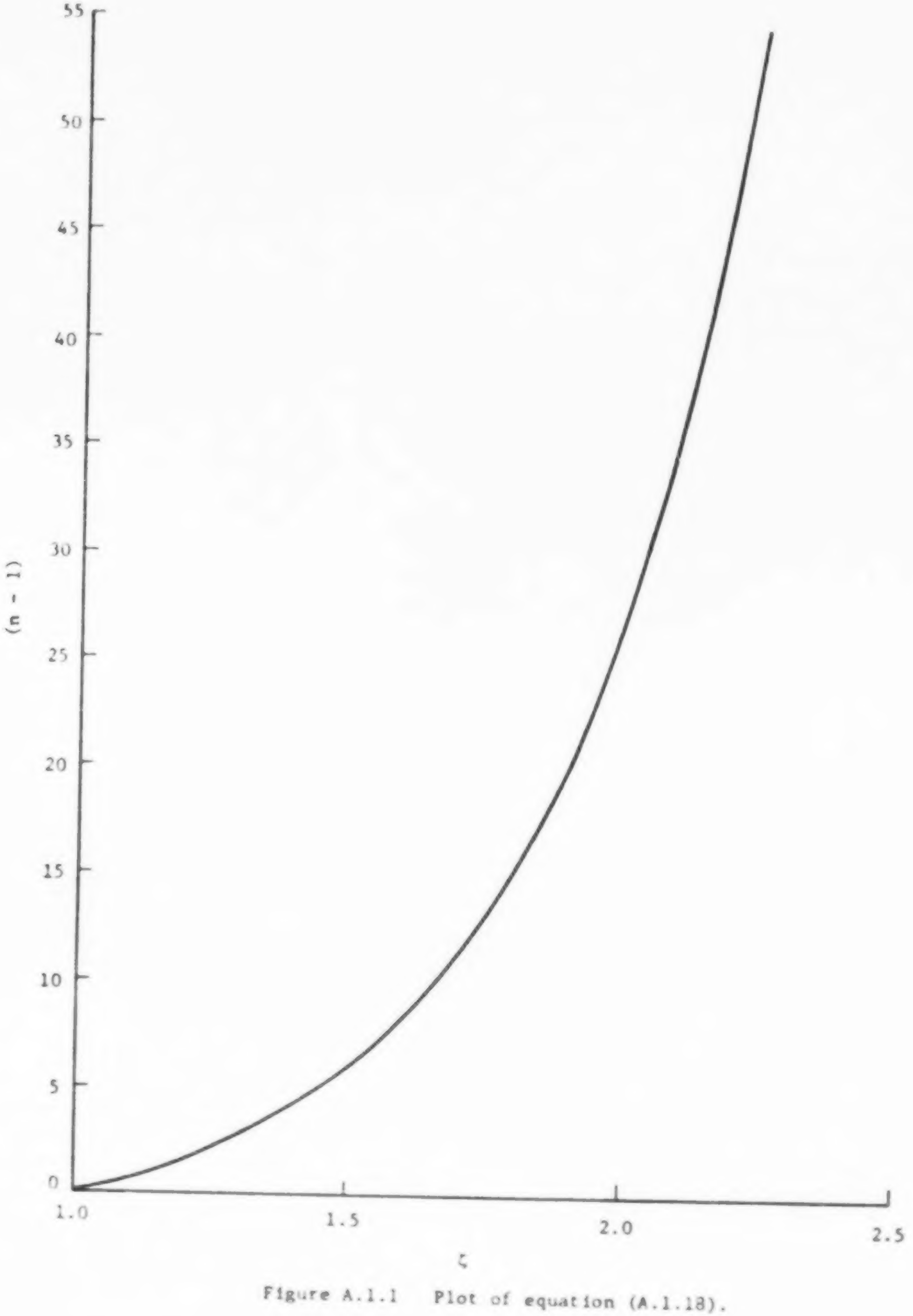

Figure A.1.1 Plot of equation (A.1.18).

A.2 THE LOGNORMAL CASE

In the lognormal case*, if x_i are the measurements, then

$$y_i = \ell n\ x_i \sim \mathcal{N}(\mu,\sigma^2) \tag{A.2.1}$$

and $\Theta = [\mu,\sigma]$ is the unknown parameter. Note that μ and σ are the mean and standard deviation of the logs of the measurements rather than of the measurements as in the normal case. Assume that the statistic is, as before

$$z = [m, \xi] \tag{A.2.2}$$

i.e., the sample mean of the measurements, m, and the largest measurement

$$\xi = \max\{x_1,\ldots,x_n\} \tag{A.2.3}$$

The estimate of the mean of x_i is taken to be the sample mean m, therefore

$$m = E\{x_i\} = \exp\left\{\hat{\mu} + \frac{\sigma^2}{2}\right\} \tag{A.2.4}$$

or

$$\hat{\mu} + \frac{\sigma^2}{2} = \ell n\ m \tag{A.2.5}$$

The maximum likelihood estimate of σ is obtained by maximizing

$$p\left(\xi \,\middle|\, \mu = \left(\ell n\ m - \frac{\sigma^2}{2}\right),\ \sigma\right) \tag{A.2.6}$$

---

*Natural logarithms are used throughout the derivation. The final results are given in terms of common logrithms.

with respect to σ. First, the distribution of ξ is

$$P\{\max(x_1,\ldots,x_n) \le \xi\} = P\{\max(y_1,\ldots,y_n) \le \ln \xi\} \qquad \text{(A.2.7)}$$

$$= F^n\left(\frac{\ln \xi - \mu}{\sigma}\right)$$

where F is the standard Gaussian distribution (A.1.6). Therefore, denoting

$$\rho \triangleq \frac{\xi}{m} \qquad \text{(A.2.8a)}$$

$$\eta \triangleq \frac{\ln \xi - \mu}{\sigma} = \frac{\ln \xi - \ln m + (\sigma^2/2)}{\sigma} \qquad \text{(A.2.8b)}$$

$$= \frac{\ln \rho + (\sigma^2/2)}{\sigma}$$

the density of ξ is

$$p(\xi|\mu,\sigma) = \frac{d}{d\xi} F^n(\eta)$$

$$= n\, F^{n-1}(\eta)\; f(\eta)\frac{d\eta}{d\xi} \qquad \text{(A.2.9)}$$

From (A.2.8b) one has

$$\frac{d\eta}{d\xi} = \frac{1}{\sigma\xi} \qquad \text{(A.2.10)}$$

Combining (A.2.9) and (A.2.10) yields

$$p(\xi|\mu,\sigma) = n\, F^{n-1}(\eta)\; f(\eta)\; (\sigma\xi)^{-1} \qquad \text{(A.2.11)}$$

The likelihood equation is, therefore

$$\frac{d}{d\sigma} p\ (\xi|\mu,\sigma) = \Big[n(n-1)F^{n-2}(\eta)\ f^2(\eta)\ (\sigma\xi)^{-1}$$

$$- n\ F^{n-1}(\eta)\eta\ f(\eta)(\sigma\xi)^{-1}\Big]\frac{d\eta}{d\sigma} \qquad \text{(A.2.12)}$$

$$- n\ F^{n-1}(\eta)\ f(\eta)\ \sigma^{-2}\ \xi^{-1} = 0$$

where use has been made of (A.1.16). Also

$$\frac{d\eta}{d\sigma} = \frac{\sigma^2 - [\ell n\ \rho + (\sigma^2/2)]}{\sigma^2} = 1 - \frac{\eta}{\sigma} \qquad \text{(A.2.13)}$$

Inserting (A.2.13) into (A.2.12) yields the following equation for σ

$$[(n-1)\ f(\eta)\ -\ F(\eta)\eta]\ (\sigma - \eta) - F(\eta) = 0 \qquad \text{(A.2.14)}$$

where $\eta = \eta(\sigma)$ according to (A.2.8b).

The solution $\hat{\sigma}$ of (A.2.14) for common logarithms is presented graphically in Figure A.2.1 as a function of the number of measurements n and the ratio ρ between the maximum and the mean. For example, assume m = 10, ξ = 30 and n = 30. Then ρ =3 and $\hat{\sigma}$ = 0.27. The estimate $\hat{\mu}$ is obtained using (A.2.5):

$$\hat{\mu} = \log m - \ell n 10\,\frac{\hat{\sigma}^2}{2} = 1 - (2.3)(0.0365) = 0.916$$

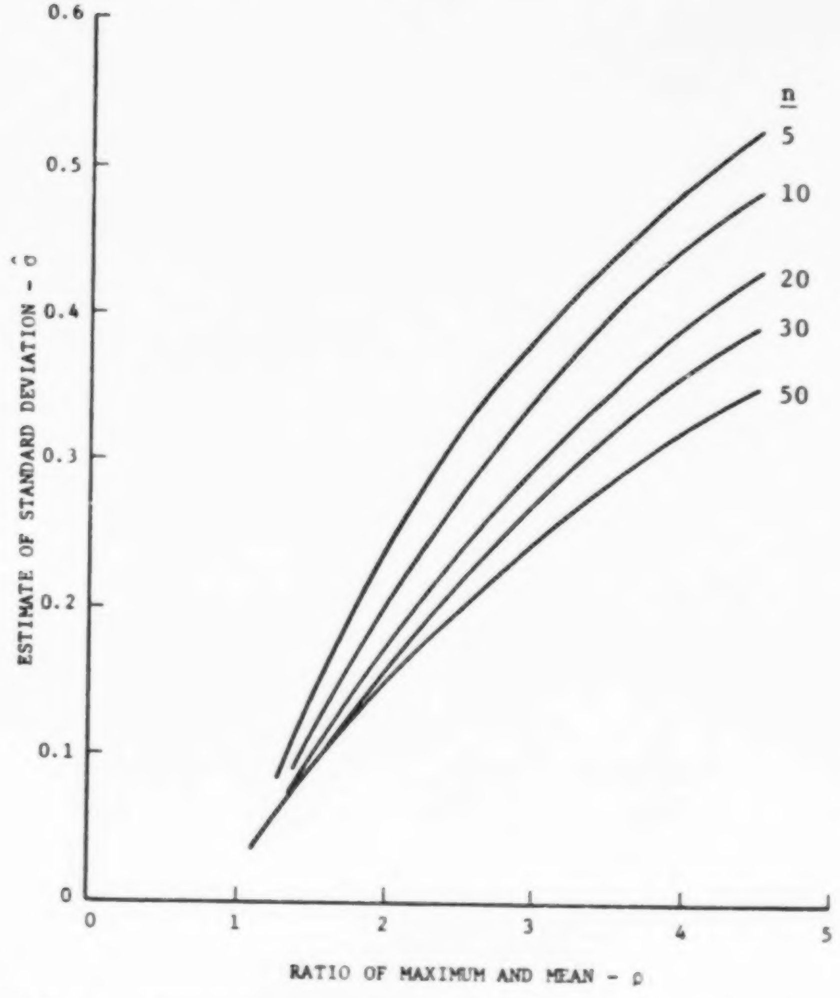

Figure A.2.1 Maximum likelihood estimate of standard deviation from mean and maximum in lognormal case.

A.3 ESTIMATE OF MEAN AND STANDARD DEVIATION FROM MAXIMUM AND MINIMUM

Let $x_1,\ldots,x_N$ be independent samples from a normal $\mathcal{N}(\mu,\sigma^2)$ distribution and let $y_1 = \min(x_1,\ldots,x_n)$ and $y_N = \max(x_1,\ldots,x_N)$. Then simple estimates of μ and σ can be obtained from the midrange $m = (y_1 + y_N)/2$ and the range $R = y_N - y_1$.

Estimate of Mean

The obvious estimate of the mean is the midrange. Kendall and Stuart [A1] gives the relative efficiency of this estimate as compared to the efficiency of the sample mean for several values of N (see Table A.3.1).

Table A.3.1 RELATIVE EFFICIENCY OF MIDRANGE AS AN ESTIMATE OF μ

N	Relative efficiency	N	Relative efficiency
2	1.000	10	.734
4	.915	20	.591
6	.840	∞	0

Estimate of Standard Deviation

The estimate of the standard deviation from y_1 and y_N has historically [A2], [A3] been in the form

$$\hat{\sigma} = R/C_N \tag{A.3.1}$$

where R is the range and $C_N = E(\tilde{R})$ where $\tilde{R}$ is the range of N samples for a $\mathcal{N}(0,1)$ distribution. $\hat{\sigma}$ is therefore an unbiased estimate of σ. A table of C_N versus N is given in Table A.3.2 [A3].

Table A.3.2. C_N VERSUS N

N	C_N	N	C_N
0	-	21	3.778
1	-	22	3.819
2	1.128	23	3.858
3	1.693	24	3.895
4	2.059	25	3.930
5	2.326	26	3.964
6	2.534	27	3.997
7	2.704	28	4.027
8	2.847	29	4.057
9	2.970	30	4.086
10	3.078	31	4.113
11	3.173	32	4.139
12	3.258	33	4.165
13	3.336	34	4.189
14	3.407	35	4.213
15	3.472	36	4.236
16	3.532	37	4.259
17	3.588	38	4.280
18	3.640	39	4.301
19	3.689	40	4.322
20	3.735		

In [A4], the relative efficiency of this estimate is given as compared to the efficiency of the sample standard deviation. Several values are shown in Table A.3.3.

TABLE A.3.3 RELATIVE EFFICIENCY OF THE ESTIMATE σ

N	Relative efficiency	N	Relative efficiency
2	1.000	10	0.850
4	0.975	20	0.700
6	0.933	50	0.490

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APPENDIX B

INVESTIGATION OF THE CORRELATION BETWEEN EFFLUENT CONSTITUENTS

In this appendix a procedure is presented to test for the uncorrelatedness of normal random variables with unknown mean and unknown variance. Subsequently, it is applied to data from the Palo Alto Municipal Waste Treatment Plant.

B.1 THE UNCORRELATEDNESS TEST

Consider two normal random variables x, and y, from which n independent samples x_i, $i = 1, \ldots, n$ and y_i, $i = 1, \ldots, n$ are available. The true means and variances are unknown and can be estimated by the well-known equations

$$\bar{x} = \frac{1}{n} \sum x_i, \qquad \bar{y} = \frac{1}{n} \sum y_i$$
$$s_x^2 = \frac{1}{n} \sum (x_i - \bar{x})^2, \quad s_y^2 = \frac{1}{n} \sum (y_i - \bar{y})^2 \tag{B.1.1}$$

We want to test whether their correlation

$$\rho \triangleq \frac{E\,[(x - Ex)\ (y - Ey)]}{[E\,(x - Ex)^2\ E(y - Ey)^2]^{1/2}} \tag{B.1.2}$$

is zero or not, i.e.,

$$H_0 : \rho = 0 \tag{B.1.3}$$

vs.

$$H_1 : \rho \neq 0 \tag{B.1.4}$$

Define the sample correlation as

$$r \triangleq \frac{1}{ns_x s_y} \sum (x_i - \bar{x})(y_i - \bar{y}) \tag{B.1.5}$$

It has been pointed out in Kendall and Stuart [B1] that the distribution of this sample correlation converges very slowly to the normal and thus a test based on the normality assumption is not accurate. The exact test is presented next. As shown in [B1]

$$t = \left[\frac{(n-2)r^2}{1-r^2}\right] \tag{B.1.6}$$

has a t-distribution with $\nu = n-2$ degrees of freedom. Thus the above simple transformation enables one to test H_o against H_1 using readily available tables.

To illustrate the procedure, consider for example $n = 30$. The t values corresponding to various values of the sample correlation r are presented in Table B.1.1. Also, the significance levels above which H_o would be rejected (and H_1 accepted) for these values of r are given.

Table B.1.1 UNCORRELATEDNESS TEST FOR N=30 SAMPLES

r	t	α%
0.5	3.06	<1
0.4	2.31	3
0.35	1.99	6
0.3	1.66	11
0.25	1.37	18

If the observed value is $r = 0.35$, then at 5% level of significance (probability of error of type I) H_o would be accepted.

B.2 EXAMPLE OF UNCORRELATEDNESS TESTS FOR EFFLUENT CONSTITUEN

Tests were run on a number of constituents from the Palo Alto Municipal Waste Treatment Plant. The data consisted of daily composite samples of the following

1. Flow
2. Suspended Solids
3. BOD (Biological Oxygen Demand)
4. TOC (Total Organic Carbon)
5. COD (Chemical Oxygen Demand)

Data was obtained from a dry month (July 1973) and a wet month (November 1973) each with 30 samples. The correlation coefficients were computed for the actual measurements, under the normal assumption and for the logarithms of the measurements, under the lognormal assumption. (The goodness of these assumptions was examined in Section V.1).

The resulting correlation coefficients are presented in Tables B.2.1 and B.2.2. An examination of these tables reveals that the sample correlations are such that only at relatively low significance levels ($\alpha = 1\%$) would the hypothesis of uncorrelatedness be accepted in some cases. This can be seen from the uncorrelatedness test illustrated in Table B.2.1. However, the variation of the correlation coefficients seems to be large from season to season and no clear pattern seems to emerge. For example, the r_{23} term (SS vs. BOD) is positive in a dry month while in a wet month it can become negative. Also notice that there is no appreciable difference in the correlation tests when done under normal or lognormal assumption. The hypothesis that the effluent constituents are highly (near unity) correlated is even less likely than their being uncorrelated.

Table B.2.1 SAMPLE CORRELATIONS OF THE MEASUREMENTS

Month	Variable sampled	2	3	4	5
Dry	1	0.28	0.33	0.55	0.58
	2		0.46	0.39	0.62
	3			0.43	0.50
	4				0.47
Wet	1	-0.24	0.45	0.29	0.22
	2		-0.19	0.27	0.25
	3			0.35	0.13
	4				0.51

Table B.2.2 SAMPLE CORRELATIONS OF LOGS OF THE MEASUREMENTS

Month	Variable sampled	2	3	4	5
Dry	1	0.30	0.32	0.58	0.60
	2		0.45	0.40	0.68
	3			0.51	0.45
	4				0.49
Wet	1	-0.24	0.50	0.28	0.23
	2		-0.18	0.37	0.33
	3			0.30	0.10
	4				0.59

REFERENCE

B1. Kendall, M. and Stuart, A., The Advanced Theory of Statistics, Volume 2, Hafner Publishing Company, New York, 1967.

APPENDIX C

EXPECTED DAMAGE AND PROBABILITY OF VIOLATION CALCULATIONS

C.1 INTRODUCTION

The sampling frequencies to choose, in determining whom to monitor, minimize the "cost" of undetected violations. This "cost" was derived in Section VI to be:

$$C = \sum_{\substack{\text{sources} \\ i}} c_i \, p_i^{s_i} \tag{C.1.1}$$

where c_i is the expected damage caused by the i^{th} source, p_i is the probability that the i^{th} source will not violate any effluent standard, and s_i is the number of times the i^{th} source is to be monitored. c_i equals the maximum of the expected damages due to the various constituents of the i^{th} source, or

$$c_i = \max_j D_{ij} \tag{C.1.2}$$

where D_{ij} is the expected damage due to the j^{th} constituent of the i^{th} source. p_i, assuming independence between the various constituents, is

$$p_i = \prod_j p_{ij} \tag{C.1.3}$$

where p_{ij} is the probability the standard on the j^{th} constituent is not violated. If the constituents are completely correlated, then

$$P_i = \min_j P_{ij} \qquad (C.1.4)$$

This appendix describes in detail both the calculation of the expected damage, D_{ij}, due to constituent j from source i and P_{ij}, the probability that constituent j, source i, does not violate its standard. It is organized as follows: Section C.2 calculates D_{ij} and P_{ij} under the assumption that only one set of effluent standards is given for the source. This corresponds to the case where there is only one outfall or the permits are written for the combined discharge from several outfalls. Section C.3 describes how these calculations are generalized to the case when standards are set for many outfalls from a single industry or municipal treatment plant. Section C.4 evaluates certain integrals that arise often in the expected damage and probability of violation calculation.

C.2 EXPECTED DAMAGE AND PROBABILITY OF VIOLATION DERIVATION: ONE SET OF STANDARDS

This section describes the derivation of the expected damage from a source and the probability of violation when there is either a single outfall from the source or there are several outfalls, all to the same river, and there is one set of standards for the total discharge from the source. When there are several outfalls but only one set of standards for the total effluent, the monthly self-monitoring reports are on the total effluent, and so the several outfalls can be treated as one.

The section is divided into four subsections. The first subsection considers the majority of constituents. All the calculations needed to determine the expected damage and probability of violation for this set of constituents are the same. pH, BOD, and temperature require slightly different calculations, and they will be treated separately in the remaining subsections.

C.2.1 Noncoupled Constituents

This subsection derives expected damage and probability of violation for all the indicators listed in Table 6.1 except pH, temperature, and dissolved oxygen.

Inputs

The data needed to calculate expected damage and probability of violation are:

For source i:

P_i = index set of pollutants
μ_{ij} = mean of mass loading of j^{th} pollutant (kg)
σ_{ij} = standard deviation of mass loading of j^{th} pollutant (kg)
γ_{ij} = distribution of j^{th} pollutant--normal or lognormal
QU_i = flow of stream above source (Ml/day)
QS_i = effluent flow (Ml/day)
CU_{ij} = concentration of the pollutant upstream from source (mg/l)
$EFST_{ij}$ = effluent standard for j^{th} pollutant (kg)

For each pollutant j:

$d_j(k)$ = concentration of pollutant when damage equals 2(k-1), k = 1, 2, ..., 6.

$d_j(k)$ is the value of the abscissa of the damage function at the k^{th} breakpoint. The damage function breakpoints for the constituents of interest were given in Table 6.1. The damage function of the j^{th} pollutant is then

$$D_j(\alpha) = \sum_{k=1}^{5} \left\{ \frac{2(\alpha - d_j(k))}{(d_j(k+1) - d_j(k))} + 2(k-1) \right\} \quad \phi(d(k), d(k+1), \alpha)$$

$$+ \; 10 \; \phi(d(6), \infty, \alpha) \qquad \text{(C.2.1)}$$

where α is the concentration of pollutant and ϕ is the characteristic function:

$$\phi(x, y, \alpha) = \begin{cases} 1 & ; \quad x \leq \alpha < y \\ 0 & ; \quad \text{otherwise.} \end{cases} \qquad \text{(C.2.2)}$$

Maximum Downstream Concentration

The maximum downstream concentration for the j^{th} pollutant - i^{th} source is given by the conservation law:

$$CO_{ij} = \frac{M_{ij} + CU_{ij}\, QU_i}{QU_i + QS_i} \qquad \text{(C.2.3)}$$

where M_{ij} is the mass loading of the j^{th} pollutant - i^{th} source (M_{ij} is a random variable with mean μ_{ij}, standard deviation σ_{ij} and distributional form γ_{ij}) and CU_{ij} is the concentration of the j^{th} pollutant upstream from the i^{th} source. (C.2.3) can be rewritten to yield

$$CO_{ij} = a_i M_{ij} + b_{ij} \qquad \text{(C.2.4a)}$$

where

$$a_i = 1/(QU_i + QS_i) \qquad \text{(C.2.4b)}$$

and

$$b_{ij} = CU_{ij} \left(\frac{QU_i}{QU_i + QS_i} \right) \tag{C.2.4c}$$

Expected Damage

The expected damage due to pollutant j from the i^{th} source is then

$$\begin{aligned} D_{ij} &= E(D_j(CO_{ij})) \\ &= \int D_j(CO_{ij}) \, \phi_{ij}(M) \, dM \end{aligned} \tag{C.2.5}$$

where $E(\cdot)$ is the expectation operator and ϕ_{ij} is the probability density function of the mass loading M_{ij}. Using (C.2.4),

$$D_{ij} = \int D_j(a_i M + b_{ij}) \, \phi_{ij}(M) \, dM \tag{C.2.6}$$

Combining (C.2.1) and (C.2.6),

$$D_{ij} = \sum_{k=1}^{6} \int_{\alpha_{ijk}}^{\beta_{ijk}} \left\{ e_{ijk} M + f_{ijk} \right\} \phi_{ij}(M) \, dM \tag{C.2.7a}$$

where

$$\alpha_{ijk} = \frac{d_j(k) - b_{ij}}{a_i} \qquad k = 1, 2, \ldots, 6 \tag{C.2.7b}$$

$$\beta_{ijk} = \begin{cases} \dfrac{d_j(k+1) - b_{ij}}{a_i} & ; \quad k = 1, 2, \ldots, 5 \\ \infty & ; \quad k = 6 \end{cases} \tag{C.2.7c}$$

$$e_{ijk} = \begin{cases} 2a_i/(d_j(k+1) - d_j(k)) & ; \quad k = 1,2,\ldots,5 \\ 0 & ; \quad k = 6 \end{cases} \qquad \text{(C.2.7d)}$$

$$f_{ijk} = \begin{cases} \dfrac{2(b_{ij} - d_j(k))}{(d_j(k+1) - d_j(k))} + 2(k-1) & ; \quad k = 1,\ldots,5 \\ 10 & ; \quad k = 6 \end{cases} \qquad \text{(C.2.7e)}$$

If α_{ijk} or β_{ijk} are less than 0, set them to 0. (C.2.7) can be rewritten

$$D_{ij} = \sum_{k=1}^{6} I_{\gamma_{ij}}(e_{ijk}, f_{ijk}, \alpha_{ijk}, \beta_{ijk}, \mu_{ij}, \sigma_{ij}) \qquad \text{(C.2.8)}$$

where

$$I_{\gamma}(e, f, \alpha, \beta, \mu, \sigma) = \int_{\alpha}^{\beta} (ex + f)\, \phi_{\gamma}(x)\, dx \qquad \text{(C.2.9)}$$

and where ϕ_γ is the normal density function with mean μ and variance σ^2 if γ = Normal, and is lognormal, with mean and variance of corresponding normal distribution being μ and σ^2, respectively, if γ = Lognormal. (C.2.9) is evaluated in Section C.4 for the normal and lognormal cases.

Probability of a Violation

The probability that a standard for the j^{th} pollutant i^{th} source is not violated is

$$P_{ij} = \int_{-\infty}^{EFST_{ij}} \phi_{ij}(M)\, dM$$

$$= I_{\gamma_{ij}}(0, 1, -\infty, EFST_{ij}, \mu_{ij}, \sigma_{ij}) \qquad \text{(C.2.10)}$$

where I_γ is defined in (C.2.9)

C.2.2 5-Day Biochemical Oxygen Demand - BOD_5

The presence of BOD_5 in the water causes a depletion in the dissolved oxygen (DO). The difference between the saturated level of dissolved oxygen, DOSAT, in the water and the actual level is called the dissolved oxygen deficit or DO-deficit. The degree of depletion caused by a given amount of BOD_5 from a source depends on several stream parameters such as stream depth, flow rate, temperature, and the distance downstream from the source. The relationship between BOD_5 and DO-deficit can be expressed (see Section VI.1) in the form

$$D_{max} = K_{BOD-DO} CO \tag{C.2.11}$$

where CO is the concentration of BOD_5 at the source, D_{max} is the maximum DO deficit downstream from the source, and K_{BOD-DO} is the BOD_5-DO transfer coefficient.

Inputs

The data needed to calculate the expected damage and probability of violation due to BOD_5 is:

For source i:

$\mu_{i,BOD}$ = mean of mass loading of BOD_5 (kg)
$\sigma_{i,BOD}$ = standard deviation of mass loading of BOD_5 (kg)
$\gamma_{i,BOD}$ = distribution of mass loading of BOD_5
$CS_{i,DO}$ = mean of DO concentration of the source (mg/l)
K_{BOD-DO_i} = BOD_5-DO transfer coefficient

QU_i = flow of stream above source (Ml/day)

QS_i = effluent flow (Ml/day)

$DOSAT_i$ = saturation level of DO in the stream (mg/l)

$EFST_{i,BOD}$ = effluent standard for BOD_5 (kg)

$CU_{i,BOD}$ = upstream concentration of BOD_5 (mg/l).

Maximum Downstream Concentration

The concentration of BOD at the point where the outfall empties into the stream is given by

$$CO_{i,BOD} = \frac{M_{i,BOD} + CU_{i,BOD}\ QU_i}{QU_i + QS_i} \qquad (C.2.12)$$

The concentration of DO is similarly

$$CO_{i,DO} = \frac{CS_{i,DO}\ QS_i + CU_{i,DO}\ QU_i}{QU_i + QS_i} \qquad (C.2.13)$$

$CU_{i,BOD}$ and $CU_{i,DO}$ are unknown and must be chosen in a way that is consistent with determining the sampling frequencies. It was suggested in Section VI that they be chosen so that a given level of damage will occur when the loading $M_{i,BOD}$ is zero and the concentration of DO in the source, $CS_{i,DO}$, is equal to $DOSAT_i$. Since there are two unknowns and only one requirement, the upstream DO concentration, $CU_{i,DO}$, shall be arbitrarily set equal to $DOSAT_i$. The value of $CU_{i,BOD}$ will be set to give the desired downstream DO concentration under zero load.

The minimum concentration of DO downstream from the source can be approximated by (see Section VI.1):

$$CO_{i,DOMIN} = CO_{i,DO} - K_{BOD-DO_i}\ CO_{i,BOD} \qquad (C.2.14)$$

Using (C.2.12) and (C.2.13) and noting that $CU_{i,DO} = DOSAT_i$ we obtain

$$CO_{i,DOMIN}$$

$$= \frac{CS_{i,DO}\, QS_i + (DOSAT_i - K_{BOD-DO_i}\, CU_{i,BOD})\, QU_i - K_{BOD-DO_i}\, M_{i,BOD}}{QU_i + QS_i} \tag{C.2.15}$$

or

$$CO_{i,DOMIN} = a_{i,BOD}\, M_{i,BOD} + b_{i,BOD} \tag{C.2.16a}$$

where

$$a_{i,BOD} = -\, K_{BOD-DO_i} / (QU_i + QS_i) \tag{C.2.16b}$$

and

$$b_{i,BOD} = \frac{1}{(QU_i + QS_i)} \left[CS_{i,DO} QS_i + \left(DOSAT_i - K_{BOD,DO_i} CU_{i,BOD} \right) QU_i \right] \tag{C.2.16c}$$

Probability of Violation

The probability that the BOD_5 effluent standard will not be violated is given by (C.2.10) with $j = BOD$.

C.2.3 pH

pH is a measure of the acidity (alkalinity) of a solution. It is defined as the negative of the log of the concentration[†] of H^+ ions. pOH is defined to be the negative of the log of the concentration of OH^- ions. pOH and pH are related by the equation

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[†] The concentration is in moles/liter.

$$pOH + pH = 14 \tag{C.2.17}$$

For pure water (H_2O), $pOH = pH = 7$. $pH < 7$ implies an acidic solution and $pH > 7$ implies a basic or alkaline solution. If two acidic solutions are combined, then the number of H^+ ions is equal to the sum of the H^+ ions from the two original solutions.* Similarly, if two basic solutions are combined, the number of OH^- ions add. Therefore, if, for example, we combine X liters of an acid with $pH = p_1$ and Y liters of an acid with $pH = p_2$, then the concentration of H^+ ions is

$$\frac{X\ 10^{-p_1} + Y\ 10^{-p_2}}{X + Y} \tag{C.2.18}$$

and the pH of the resulting solution is the negative log of this quantity. So, as long as both the effluent and the receiving waters are both acidic or both basic, the concentration of ions can be considered as a conservative constituent.

The standards for pH require that pH lie between two values: one above 7, the other below. The damage as measured by pH and the distributions of effluent pH can also be divided into two parts: one for $pH > 7$, the other for $pH < 7$. Similarly, to consider the worse case problem, the receiving waters will be assumed to have the same quality (acidic or basic) as the effluent.

The self-monitoring data for pH will either be (1) a monthly maximum and minimum or (2) a monthly maximum, minimum, and mean. If the data are the former, then the mean and standard deviation can be estimated using the midrange and the range respectively. If they are the latter, then two statistical descriptions can be obtained, one using the mean and maximum, the other the mean and minimum. Two standard deviations would be estimated using the estimation technique described in Appendix A.1. The probability density function for pH would have the shape shown in Figure C.2.1.

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* We are assuming that no chemical reaction or buffering takes place.

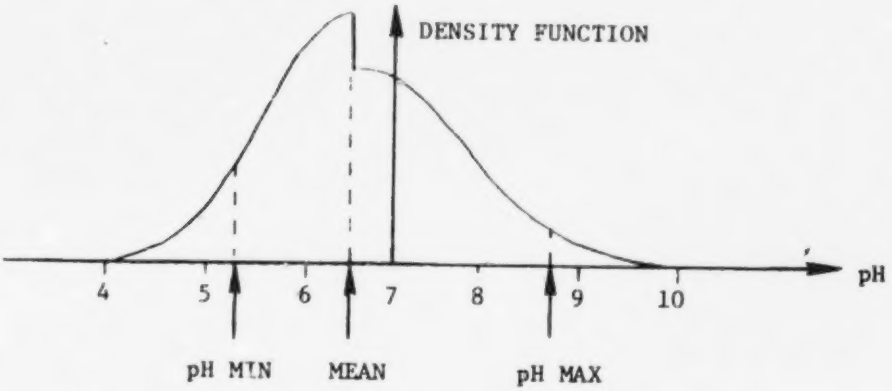

Figure C.2.1 Example of probability density function of pH.

Inputs

The data needed to calculate the expected damage and probability of violation are given below. The subscript J denotes either H or OH. The distribution of pH or pOH is assumed normal.

For source i:

μ_{iJ} = mean of pJ(μ_{iOH} = 14 - μ_{iH})

σ_{iJ} = standard deviation of pJ

CU_{iJ} = upstream concentration of J ions (Moles/l)

$EFST_{iJ}$ = effluent standard for pJ

QU_i = flow of stream upstream from source (Ml/day)

QS_i = effluent flow (Ml/day).

The damage function for pH was given in Table 6.1. It is much easier to obtain expressions for the expected damage if the damage function is given in units of concentration of ions. The damage function is therefore redefined as shown in Table C.2.1 (the damage function is assumed linear, in concentration, between the given values) and it is plotted in Figure C.2.2. Therefore, for $J = H$ or OH, the following is defined:

$d_J(k)$ = concentration of J ions when damage equals $k-1$ where $k = 1, 2, \ldots, 11$.

The damage function $D_J(\alpha)$

$$D_J(\alpha) = \sum_{k=1}^{10} \left\{ \frac{(\alpha - d_J(k))}{(d_J(k+1) - d_J(k))} + (k-1) \right\} \Phi(d(k), d(k+1), \alpha)$$

$$+ 10 \quad \Phi(d(11), \infty, \alpha) \tag{C.2.19}$$

where Φ is defined in (C.2.2).

Maximum Downstream Concentration

The maximum downstream concentration of H or OH ions is

$$CO_{iJ} = \frac{CS_{iJ}\, QS_i + CU_{iJ}\, QU_i}{QS_i + QU_i} \tag{C.2.20}$$

where CS_{iJ} is the concentration of J ions in the effluent. Note that

$$CS_{iJ} = 10^{-pJ} \tag{C.2.21}$$

where pJ is the pH or pOH of the effluent and is a normal random variable. The upstream concentration is set to give the desired level of damage under zero source load.

TABLE C.2.1 DAMAGE FUNCTION BREAKPOINTS

Damage function value	H^+ ions		OH^- ions	
	pH	Conc	pOH	Conc
0	7.00	1.00×10^{-7}	7.00	1.00×10^{-7}
1	6.75	1.78×10^{-7}	6.50	3.16×10^{-7}
2	6.50	3.16×10^{-7}	6.00	1.00×10^{-6}
3	6.25	5.62×10^{-7}	5.80	1.58×10^{-6}
4	6.00	1.00×10^{-6}	5.60	2.51×10^{-6}
5	5.50	3.16×10^{-6}	5.30	5.01×10^{-6}
6	5.00	1.00×10^{-5}	5.00	1.00×10^{-5}
7	4.50	3.16×10^{-5}	4.50	3.16×10^{-5}
8	4.00	1.00×10^{-4}	4.00	1.00×10^{-4}
9	3.95	1.12×10^{-4}	3.95	1.12×10^{-4}
10	3.90	1.26×10^{-4}	3.90	1.26×10^{-4}

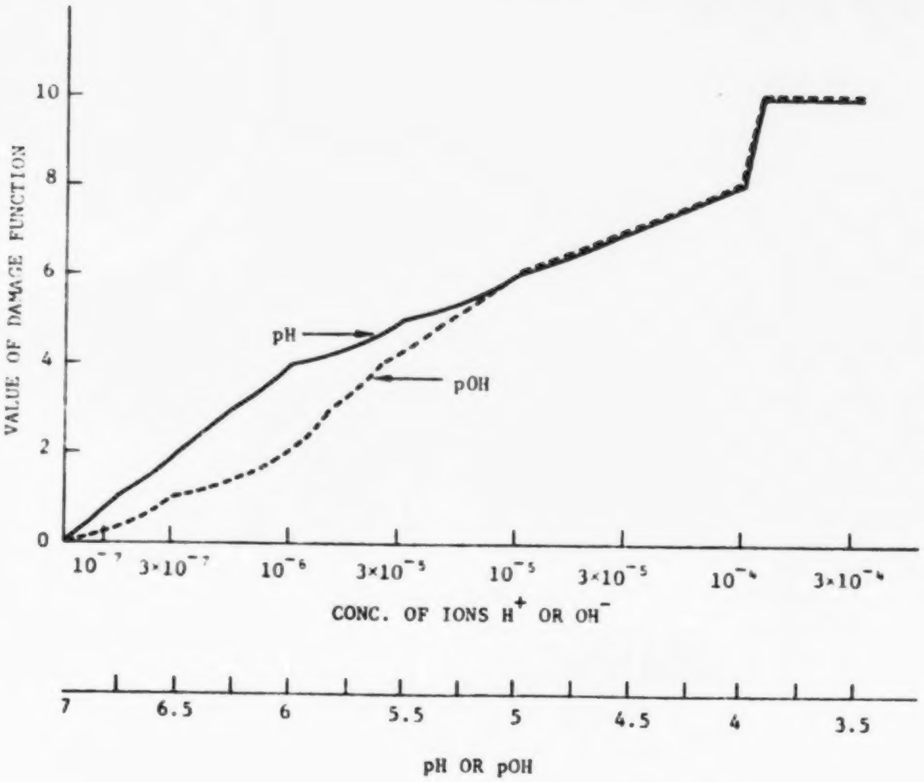

Figure C.2.2 Damage function for pH and pOH

Therefore

$$CO_{iJ} = a_{iJ}\,10^{-pJ} + b_{iJ} \qquad \text{(C.2.22a)}$$

where

$$a_{iJ} = QS_i/(QU_i + QS_i) \qquad \text{(C.2.22b)}$$

$$b_{iJ} = CU_{iJ}\left(\frac{QU_i}{QU_i + QS_i}\right) \qquad \text{(C.2.22c)}$$

Expected Damage

The expected damage can be separated into two parts--the damage due to H^+ ions and the damage due to OH^- ions. Let q_i be the density function for pH for the i^{th} source. Define

$$\phi_{iH}(x) = \begin{cases} q_i(x) & ; \quad x \le 7 \\ 0 & ; \quad x \ge 7 \end{cases}$$

$$\phi_{iOH}(x) = \begin{cases} q_i(14-x) & ; \quad x \le 7 \\ 0 & ; \quad x \ge 7 \end{cases} \qquad \text{(C.2.23)}$$

Then the damage due to J ions (where $J = OH^-$ or H^+) is

$$D_{iJ} = \int_0^7 D_J(CO_{iJ})\,\phi_{iJ}(pJ)\,dpJ \qquad \text{(C.2.24)}$$

and the total damage associated with pH is $D_{iH} + D_{iOH}$.

As discussed earlier, the density function can, depending on the input data, be described by a mean value and either one or two values of standard deviation (see Figure C.2.1 for an example of the latter distribution). First consider the case when the distribution is described by a single standard deviation. Using (C.2.22a), (C.2.24) becomes

$$D_{iJ} = \int_{0}^{7} D_J(a_{iJ}\, 10^{-pJ} + b_{iJ})\ \phi_{iJ}(pJ)\ dpJ \qquad \text{(C.2.25)}$$

where ϕ_{iJ} is a normal random density function with mean μ_{iJ} and standard deviation σ_{iJ}. Making a change of variables, let $w = 10^{-pJ}$; then

$$D_{iJ} = \int_{10-7}^{1} D_J(a_{iJ}\, w + b_{iJ})\ g_{iJ}(w)\ dw \qquad \text{(C.2.26)}$$

where g_{iJ} is a lognormal density function with corresponding normal distribution having mean $-\mu_{iJ}$ and standard deviation σ_{iJ}. Analogous to the derivation of (C.2.7) we obtain

$$D_{iJ} = \sum_{k=1}^{11} \int_{\alpha_{iJk}}^{\beta_{iJk}} \left\{ e_{iJk}\, w + f_{iJk} \right\} g_{iJ}(w)\ dw \qquad \text{(C.2.27)}$$

where

$$\alpha_{iJk} = \frac{d_J(k) - b_{iJ}}{a_{iJ}} \quad ; \quad k = 1, 2, \ldots, 11 \qquad \text{(C.2.27a)}$$

$$\beta_{iJk} = \begin{cases} (d_J(k+1) - b_{iJ})/a_{iJ} & ; \quad k = 1, 2, \ldots, 10 \\ \infty & ; \quad k = 11 \end{cases} \qquad \text{(C.2.27b)}$$

If $\alpha_{iJk} < 10^{-7}$, then reset $\alpha_{iJk} = 10^{-7}$ and $\beta_{iJ(k-1)} = 10^{-7}$. If $\beta_{iJk} > 1$, then reset $\beta_{iJk} = 1$ and $\alpha_{iJ(k+1)} = 1$. Also

$$e_{iJk} = \begin{cases} a_i/(d_J(k+1) - d_J(k)) & ; \quad k=1,\ 2,\ \ldots,\ 10 \\ 0 & ; \quad k=11 \end{cases} \qquad \text{(C.2.27c)}$$

$$f_{iJk} = \begin{cases} \dfrac{(b_{iJ} - d_J(k))}{(d_J(k+1) - d_J(k))} + (k-1) & ; \quad k=1,\ 2,\ \ldots,\ 10 \\ 10 & ; \quad k=11 \end{cases} \qquad \text{(C.2.27d)}$$

(C.2.27) can be rewritten

$$D_{iJ} = \sum_{k=1}^{11} I_L(e_{iJk},\ f_{iJk},\ \alpha_{iJk},\ \beta_{iJk},\ -\mu_{iJ},\ \sigma_{iJ}) \qquad \text{(C.2.28)}$$

where I_L is defined in Section C.4.

Now consider the case when the density function is of the form shown in Figure C.2.1 (i.e., the density is defined in terms of a mean μ_{iH} and two standard deviations σ_{iH} and σ_{iOH}). Then the density function for pH can be written

$$\begin{aligned} q_i(x) &= q_i(x)\ \Phi(-\infty,\ \mu_{iH},\ x) + q_i(x)\ \Phi(\mu_{iH},\ \infty,\ x) \\ &= q_{iH}(x) + q_{iOH}(x) \end{aligned} \qquad \text{(C.2.29)}$$

where Φ is the characteristic function defined in (C.2.2). $q_{iH}(x)$ is the result when a normal density function with mean μ_{iH} and standard deviation σ_{iH} is restricted to the range $x \leq \mu_{iH}$ and set to zero for $x > \mu_{iH}$. q_{iOH} is similarly defined.

There are two cases to consider: $\mu_{iH} \leq 7$ or $\mu_{iH} > 7$. First suppose $\mu_{iH} > 7$, then using (C.2.23)

$$\phi_{iH}(x) = \begin{cases} q_{iH}(x) & ; \quad x \le 7 \\ 0 & ; \quad x > 7 \end{cases} \tag{C.2.30a}$$

and

$$\phi_{iOH}(x) = \begin{cases} q_{iOH}(14 - x) & ; \quad x < \mu_{iOH} \\ q_{iH}(14 - x) & ; \quad \mu_{iOH} \le x \le 7 \\ 0 & ; \quad x > 7 \end{cases} \tag{C.2.30b}$$

For this case, the formula for D_{iH} is given by (C.2.27). D_{iOH}, however, is now (analogous to (C.2.25))

$$\begin{aligned} D_{iOH} &= \int_0^{\mu_{iOH}} D_J(a_{iOH}10^{-pJ} + b_{iOH})\, q_{iOH}(14 - pJ)dpJ \\ &+ \int_{\mu_{iOH}}^{7} D_J(a_{iOH}10^{-pJ} + b_{iOH})\, q_{iH}(14 - pJ)dpJ \\ &= \int_{10^{-7}}^{10^{-\mu_{iOH}}} D_J(a_{iOH}w + b_{iOH})\, \psi_{iH}(w)dw \\ &+ \int_{10^{-\mu_{iOH}}}^{1} D_J(a_{iOH}w + b_{iOH})\, \psi_{iOH}(w)dw \end{aligned} \tag{C.2.31}$$

where ψ_{iH} and ψ_{iOH} are lognormal density functions whose corresponding normal distributions have mean $-\mu_{iOH}$ and standard deviations σ_{iH} and σ_{iOH} respectively. Using (C.2.19), (C.2.31) becomes

$$
\begin{aligned}
D_{iOH} &= \sum_{k=1}^{\ell_i-1} \int_{\alpha_{iOHk}}^{\beta_{iOHk}} \left\{ e_{iOHk} w + b_{iOHk} \right\} \psi_{iH}(w)\,dw \\
&\quad + \int_{\alpha_{iOH\ell_i}}^{10^{-\mu_{iOH}}} \left\{ e_{iOH\ell_i} w + b_{iOH\ell_i} \right\} \psi_{iH}(w)\,dw \\
&\quad + \int_{10^{-\mu_{iOH}}}^{\beta_{iOH\ell_i}} \left\{ e_{iOH\ell_i} w + b_{iOH\ell_i} \right\} \psi_{iOH}(w)\,dw \\
&\quad + \sum_{k=\ell_i+1}^{11} \int_{\alpha_{iOHk}}^{\beta_{iOHk}} \left\{ e_{iOHk} w + b_{iOHk} \right\} \psi_{iOH}(w)\,dw \\
&= \sum_{k=1}^{\ell_i-1} I_L(e_{iOHk}, f_{iOHk}, \alpha_{iOHk}, \beta_{iOHk}, -\mu_{iOH}, \sigma_{iH}) \\
&\quad + I_L(e_{iOH\ell_i}, f_{iOH\ell_i}, \alpha_{iOH\ell_i}, 10^{-\mu_{iOH}}, -\mu_{iOH}, \sigma_{iH}) \\
&\quad + I_L(e_{iOH\ell_i}, f_{iOH\ell_i}, 10^{-\mu_{iOH}}, \beta_{iOH\ell_i}, -\mu_{iOH}, \sigma_{iOH}) \\
&\quad + \sum_{k=\ell_i+1}^{11} I_L(e_{iOHk}, f_{iOHk}, \alpha_{iOHk}, \beta_{iOHk}, -\mu_{iOH}, \sigma_{iOH})
\end{aligned}
\tag{C.2.32}
$$

where $\ell_i \in \{1, 2, \ldots, 11\}$ is defined so that $\alpha_{iOH\ell_i} \leq 10^{-\mu_{iOH}} < \beta_{iOH\ell_i}$. Analogously if $\mu_{iH} \leq 7$, then the equation for D_{iOH} is given by (C.2.27), and D_{iH} becomes

$$
\begin{aligned}
D_{iH} = & \sum_{k=1}^{\ell_i - 1} I_L(e_{iHk}, f_{iHk}, \alpha_{iHk}, \beta_{iHk}, -\mu_{iH}, \sigma_{iOH}) \\
& + I_L(e_{iH\ell_i}, f_{iH\ell_i}, \alpha_{iH\ell_i}, 10^{-\mu_{iH}}, -\mu_{iH}, \sigma_{iOH}) \\
& + I_L(e_{iH\ell_i}, f_{iH\ell_i}, 10^{-\mu_{iH}}, \beta_{iH\ell_i}, -\mu_{iH}, \sigma_{iH}) \\
& + \sum_{k=\ell_{i+1}}^{11} I_L(e_{iHk}, f_{iHk}, \alpha_{iHk}, \beta_{iHk}, -\mu_{iH}, \sigma_{iH})
\end{aligned}
$$

where $\ell_i \in \{1, 2, \ldots, 11\}$ satisfies $\alpha_{iH\ell_i} \leq 10^{-\mu_{iH}} \leq \beta_{iH\ell_i}$.

Probability of Violation

The probability that the standard for either pH or pOH, for the i^{th} source, is violated is

$$\rho_{iJ} = \int_{-\infty}^{EFST_{iJ}} \phi_{iJ}(pJ)dpJ \tag{C.2.34}$$

where ϕ_{iJ} is given by (C.2.23).

For the case where the probability distribution is defined by a mean $\mu_{iH}(\mu_{iOH} = 14 - \mu_{iH})$ and a single standard deviation $\sigma_{iH} = \sigma_{iOH}$, ρ_{iJ} is given by

$$\rho_{iJ} = I_N(0, 1, -\infty, EFST_{iJ}, \mu_{iJ}, \sigma_{iJ}) \tag{C.2.35}$$

where I_N is defined in Section C.4. The probability of no violation due to both H^+ and OH^- ions is $1 - (\rho_{iH} + \rho_{iOH})$.

Now consider the case where the density function is defined in terms of a mean and two standard deviations σ_{iH} and σ_{iOH} (see Figure C.2.1). Suppose $\mu_{iH} > 7$, then ρ_{iH} is given by (C.2.34). If $\mu_{iOH} > EFST_{iOH}$ then ρ_{iOH} is also given by (C.2.35), otherwise

$$\rho_{iOH} = \int_{-\infty}^{\mu_{iOH}} \phi_{iOH}(x)dx + \int_{\mu_{iOH}}^{EFST_{iOH}} \phi_{iH}(x)dx$$

$$= 0.5 + I_N(0,\ 1,\ \mu_{iOH},\ EFST_{iOH},\ \mu_{iOH},\ \sigma_{iH}) \qquad (C.2.36)$$

Similarly, if $\mu_{iH} \leq 7$, then ρ_{iOH} is given by (C.2.36). If $\mu_{iH} > EFST_{iH}$, then ρ_{iH} is also given by (C.2.35), otherwise

$$\rho_{iH} = 0.5 + I_N(0,\ 1,\ \mu_{iH},\ EFST_{iH},\ \mu_{iH},\ \sigma_{iOH}) \qquad (C.2.37)$$

The probability of no violation is then $1 - (\rho_{iH} + \rho_{iOH})$.

C.2.4 Temperature

The damage due to heat from an effluent is a function of the change in temperature from its ambient value.

Inputs

The data needed to calculate expected damage and the probability of a violation are:

For the i^{th} source:

μ_{iT} = mean temperature change (°C)

σ_{iT} = standard deviation of the temperature change (^{o}C)

QU_i = flow of stream above source (Ml/day)

QS_i = effluent flow (Ml/day)

The damage function which is a function of the temperature change from ambient is of the same form as (C.2.1) with the breakpoints $d_T(k)$ given in Table 6.1.

Temperature Change

The temperature change or temperature difference between the influent and effluent is measured for various industries. This section specifies the calculations needed to determine expected damage and probability of a violation.

The temperature downstream from the source is

$$TO_i = \frac{TU_i \; QU_i + TS_i \; QS_i}{QU_i + QS_i} \tag{C.2.38}$$

where TS_i is the temperature of the effluent and TU_i is the upstream temperature. The change in the temperature of the river, ΔT_i, is

$$\Delta T_i = TO_i - TU_i = \frac{(TS_i - TU_i) \; QS_i}{QU_i + QS_i} \tag{C.2.39}$$

Letting $\Delta TS_i = TS_i - TU_i$ be the change between the influent and effluent temperature, we have

$$\begin{aligned} \Delta T_i &= \Delta TS_i \left(\frac{QS_i}{QU_i + QS_i} \right) \qquad \text{(C.2.40a)} \\ &= a_{iT} \; \Delta TS_i \end{aligned}$$

where

$$a_{iT} = \frac{QS_i}{QU_i + QS_i} \qquad \text{(C.2.40b)}$$

Expected Damage

The expected damage due to temperature change is

$$\begin{aligned} D_{iT} &= E(D_T(\Delta T_i)) \\ &= \int D_T(\Delta T_i)\phi_{iT}(\Delta TS)d(\Delta TS) \qquad \text{(C.2.41)} \end{aligned}$$

where ϕ_{iT} is the probability density function of the change in effluent temperature. Combining (C.2.40) and (C.2.41)

$$D_{iT} = \int D_T(a_i\Delta TS)\phi_{iT}(\Delta TS)d(\Delta TS) \qquad \text{(C.2.42)}$$

Since the damage function is in the same form as in Section C.2.1 (with $b_i = 0$), the expression for D_{iT} is the same as given by (C.2.7), (C.2.8) with $j = T$.

Probability of a Violation

The probability that the standard for temperature is not violated for source i is given by (C.2.10) with $j = T$.

C.3 EXPECTED DAMAGE AND PROBABILITY OF VIOLATION DERIVATION --SEVERAL SETS OF STANDARDS

This section describes the derivation of the expected damage from a source and the probability of violation when there are several outfalls, each with its own effluent standards. The most complicated case treated occurs when the outfalls flow into different bodies of water.

C.3.1 Inputs

The data needed to calculate expected damage and probability of violation are:

For source i:

$R_{i\ell}$ = index set of outfalls flowing into stream ℓ.

For source i, stream ℓ:

$QU_{i\ell}$ = flow of stream above source (Ml/day)
$DOSAT_{i\ell}$ = saturation level of DO in stream (mg/l)
$K_{BOD\text{-}DO_{i\ell}}$ = BOD_5 - DO transfer coefficient

For source i, outfall k:

P_{ik} = index set of pollutants
μ_{ijk} = mean of mass loading of j^{th} pollutant (kg)
σ_{ijk} = standard deviation of mass loading of j^{th} pollutant (kg)
γ_{ijk} = distribution of j^{th} pollutant
QS_{ik} = effluent flow (Ml/day)
$EFST_{ijk}$ = effluent standard for j^{th} pollutant (kg)
CU_{ijk} = upstream concentration of j^{th} pollutant (mg/l)
$\bar{\mu}_{iJk}$ = mean of pJ, J = H or OH (pH or pOH)
$\bar{\sigma}_{iJk}$ = standard deviation of pJ, J = H or OH (pH or pOH)
$EFST_{iJ}$ = effluent standard of pJ, J = H or OH (pH or pOH)

C.3.2 Expected Damage

Expected Damage on Stream ℓ - All Variables Except pH

The expected damage to a single stream depends on the total mass load of pollutants flowing into it. It is assumed here that the outfalls are located close enough together, as far as damage is concerned, for the effluents to be considered as coming from a single outfall. The following development is for all constituents except pH (pH will be treated later). It is assumed that the distribution of the j^{th} pollutant is the same for all the pipes, that is, γ_{ijk} = constant for $k \varepsilon R_{i\ell}$. The effluent flows add, therefore

$$QS'_{i\ell} = \text{total effluent flow from source i into stream } \ell$$

$$= \sum_{k \varepsilon R_{i\ell}} QS_{ik} \tag{C.3.1}$$

Normal Case - For the case where the probability distribution of the mass loadings is normal, the distribution of the total loading into stream ℓ is normal with mean and variance equal to the sum of the individual means and variances. (This is true under the assumption that the loadings are independent, which will most likely be the case, since different outfalls are almost always connected to different processes.) Therefore, for source i, stream ℓ:

$$\mu'_{ij\ell} = \text{mean of mass loading of } j^{th} \text{ pollutant}$$

$$= \sum_{k \varepsilon R_{i\ell}} \mu_{ijk} \tag{C.3.2}$$

$$(\sigma'_{ij\ell})^2 = \text{variance of mass loading of } j^{th} \text{ pollutant}$$

$$= \sum_{k \varepsilon R_{i\ell}} \sigma^2_{ijk} \tag{C.3.3}$$

Lognormal Case - In the lognormal case, the sum of lognormal random variables is no longer lognormal. In fact, the distribution is, in general, very complicated, and to use it would be untractable for our purposes. Since the mean and variance of the distribution of the total mass loading are equal to the sum of the means and variances, respectively, of the individual loadings, an approximation of the distribution can be obtained by assuming that the resulting distribution is lognormal with mean and variance equal to the sum of the means and variances respectively. This will be a very good approximation for the cases of interest.

Recalling that μ_{ijk} and σ^2_{ijk} are the mean and variance of the corresponding normal distribution, the mean, m_{ijk}, and variance, v_{ijk}, of the lognormal distribution are

$$m_{ijk} = 10^{-(\mu_{ijk} + 1/2\ \gamma\sigma^2_{ijk})} \tag{C.3.4}$$

and

$$v_{ijk} = m^2_{ijk} \left\{ 10^{\gamma\sigma^2_{ijk}} - 1 \right\} \tag{C.3.5}$$

where $\gamma = \ln 10$. The mean and variance of the total mass loading are then

$$m'_{ij\ell} = \sum_{k\varepsilon R_{i\ell}} m_{ijk} \tag{C.3.6}$$

$$v'_{ij\ell} = \sum_{k\varepsilon R_{i\ell}} v_{ijk} \tag{C.3.7}$$

Assuming that the resulting distribution is lognormal, the corresponding normal distribution has variance and mean

$$(\sigma'_{ij\ell})^2 = \frac{1}{\gamma} \log \left(\frac{v'_{ij\ell}}{(m'_{ij\ell})^2} + 1 \right) \tag{C.3.8}$$

$$\mu'_{ij\ell} = \log m'_{ij\ell} - 1/2\, \gamma(\sigma'_{ij\ell})^2 \qquad \text{(C.3.9)}$$

Expected Damage on Stream ℓ - pH

Since the distribution of pH (or pOH) is normal, the distribution of H^+ (or OH^-) ions is lognormal. Since the loadings of ions add, the distribution of pH for the total effluent into stream ℓ is very similar to the lognormal case just discussed. The major difference arises from the fact that pH is defined as the negative of the log of the concentration of ions. Thus, equations (C.3.4) through (C.3.9) hold with $\mu_{ijk} = - \bar{\mu}_{ijk}$ obtaining $\mu'_{ij\ell}$, then $\bar{\mu}'_{ij\ell} = - \mu'_{ij\ell}$.

Total Expected Damage

All the data have now been combined in terms of the total loading due to source i in stream ℓ. The formulas of Section C.2 can now be used to obtain the expected damage where all the variables have an extra subscript denoting the stream into which the outfall flows. So letting $D_{ij\ell}$ be the expected damage due to the flow of the j^{th} constituent from source i into stream ℓ, the expected damage due to the i^{th} source can then be written (analogous to (C.1.2))

$$c_i = \max_{j,\ell} D_{ij\ell} \qquad \text{(C.3.10)}$$

C.3.3 Probability of Violation

The calculation of the probability of violation is not complicated since, if we assume that the effluents from the various outfalls are independent, the probability of no violation from all the outfalls is the product of the probability of no violation in each of the outfalls. To be precise, let

p_{ijk} = probability of no violation due to pollutant j, outfall k, source i.

The calculation of p_{ijk} is discussed in Section C.2. Using (C.1.3) and (C.1.4), the probability of no violation of any standard from outfall k, source i is

$$p_{ik} = \begin{cases} \prod_{j \epsilon P_{ik}} p_{ijk} & ; \quad \text{uncorrelated constituents} \\ \min_{j \epsilon P_{ik}} p_{ijk} & ; \quad \text{correlated constituents} \end{cases} \tag{C.3.11}$$

The probability of no violation from any pollutant of any outfall for the source i is then

$$p_i = \prod_k p_{ik} \tag{C.3.12}$$

where we have assumed that the pollutant loadings in the outfalls are independent.

C.4 CALCULATION OF IMPORTANT INTEGRALS

C.4.1 Normal Case

$$I_N = I_N(a, b, \alpha, \beta, \mu, \sigma) = \int_\alpha^\beta (ax + b)\, \tilde{f}(x)dx \tag{C.4.1}$$

where $\tilde{f}$ is normal with mean μ and variance σ^2. Therefore

$$I_N = \int_\alpha^\beta \frac{ax + b}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{(x - \mu)^2}{2\sigma^2}\right\} dx$$

$$= \int_\alpha^\beta \frac{a(x - \mu) + \mu a + b}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{(x - \mu)^2}{2\sigma^2}\right\} dx \tag{C.4.2}$$

Let $\hat{x} = (x - \mu)/\sigma$, $\hat{\alpha} = (\alpha - \mu)/\sigma$ and $\hat{\beta} = (\beta - \mu)/\sigma$, then

$$I_N = \frac{1}{\sqrt{2\pi}} \int_{\hat{\alpha}}^{\hat{\beta}} \left(a\hat{x} + \frac{\mu a + b}{\sigma} \right) e^{-\hat{x}^2/2} \, \sigma d\hat{x}$$

$$= a\sigma \, [f(\hat{\alpha}) - f(\hat{\beta})] + (\mu a + b) \, [F(\hat{\beta}) - F(\hat{\alpha})] \qquad \text{(C.4.3)}$$

where F and f are, respectively, the standard normal distribution and density function with mean 0 and standard deviation 1.

C.4.2 Lognormal Case

$$I_L = I_L(a, b, \alpha, \beta, \mu, \sigma) = \int_{\alpha}^{\beta} (ay + b) \, g(y) dy$$

where g is a lognormal density function* whose corresponding normal density function has mean μ and variance σ^2. Let $\bar{\alpha} = \log \alpha$, $\bar{\beta} = \log \beta$ and $x = \log y$, then

$$I_L = \int_{\bar{\alpha}}^{\bar{\beta}} (ae^{kx} + b) \, \tilde{f}(x) dx \qquad \text{(C.4.4)}$$

where $\tilde{f}$ is normal with mean μ, variance σ^2, and where we used the identity $y = 10^x = e^{kx}$, $k = \ln 10$. Thus

$$I_L = \int_{\bar{\alpha}}^{\bar{\beta}} \frac{(ae^{kx} + b)}{\sqrt{2\pi\sigma^2}} \exp \left\{ - \frac{(x - \mu)^2}{2\sigma^2} \right\} dx \qquad \text{(C.4.5)}$$

Now

$$kx - \frac{(x - \mu)^2}{2\sigma^2} = \frac{-1}{2\sigma^2} \left(x^2 - 2x(\mu + \sigma^2 k) + \mu^2 \right)$$

$$= - \frac{\left(x - (\mu + \sigma^2 k) \right)^2}{2\sigma^2} + \frac{(2k\mu + \sigma^2 k^2)}{2} \qquad \text{(C.4.6)}$$

So

---

* $g(y) = 0$ for $y < 0$, so if α or β is less than 0, set them equal to zero for remaining calculations.

$$I_L = \int_{\bar{\alpha}}^{\bar{\beta}} \frac{a}{\sqrt{2\pi\sigma^2}} \exp\left\{k\mu + \frac{\sigma^2 k^2}{2}\right\} \exp\left\{-\frac{\left(x - (\mu + \sigma^2 k)\right)^2}{2\sigma^2}\right\} dx$$

$$+ \int_{\bar{\alpha}}^{\bar{\beta}} \frac{b}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\} dx$$

$$= a \exp\left\{k\mu + \frac{\sigma^2 k^2}{2}\right\} \left(F(\beta_2) - F(\alpha_2)\right)$$

$$+ b\left(F(\beta_1) - F(\alpha_1)\right) \qquad (C.4.7)$$

where

$$\beta_1 = \frac{\bar{\beta} - \mu}{\sigma}$$

$$\beta_2 = \frac{\bar{\beta} - (\mu + \sigma^2 k)}{\sigma} = \beta_1 - \sigma k$$

$$\alpha_1 = \frac{\bar{\alpha} - \mu}{\sigma}$$

$$\alpha_2 = \frac{\bar{\alpha} - (\mu + \sigma^2 k)}{\sigma} = \alpha_1 - \sigma k$$

and F is defined in Section C.4.1.

APPENDIX D

RESOURCES REQUIRED TO MONITOR A SOURCE

The monitoring resources, r_i, required to monitor source i include field, laboratory, office, and transportation costs. The field and laboratory costs contain costs due to manpower and equipment. Each monitoring agency should examine its costs to determine r_i, since these costs will vary due to differences in agency structure, size of regions that are in agencies' jurisdiction, etc. The purpose of this Appendix is to develop reasonable values for r_i to be used in the demonstration part of the project. The transportation costs to travel to the various sites are assumed small and will be neglected.

D.1 FIELD AND OFFICE COSTS

Estimates of manpower requirements for compliance monitoring are given in [D1]. It is estimated that it will take 8 man-days to travel to plant, set up equipment, take measurements, remove equipment, and return to point of origin. If more than 5 outfalls are to be sampled, the manpower requirements must be increased. Also, there may be some savings if additional surveys are conducted in the same vicinity. Mr. R. Christianson of the Michigan Water Resources Commission* estimated that a two man crew can make one 24-hour composite measurement in two days (including set-up and removal) and that the crew can handle four closely spaced outfalls in this period. Combining these estimates, we shall assume that it takes 2 men 2-1/2 days (or 5 man-days) to monitor 4 outfalls. We shall assume that the two man team can be divided between two sources if, at most, two outfalls are located at each source. The office cost to process the compliance monitoring data is estimated, in [1], to be 3 man-days. In addition, Mr. Christianson, estimated the equipment costs to monitor the sources at about $2,500/year. Based on these assumptions, Table D.1 gives the total cost of monitoring a source (not including laboratory costs) based on a man day costing $64.

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*Private communication.

Table D.1 TOTAL FIELD AND OFFICE COSTS

No. of outfalls	Manpower field costs	Manpower office costs	Equipment costs	Total cost
1 or 2	$320	$192	$13	$ 525
3 or 4	$640	$192	$25	$ 857
5 or 6	$960	$192	$38	$1190
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

D.2 LABORATORY COST

The laboratory costs must include both the cost of making the analyses and the costs of report writing. If a private laboratory is used, then overhead costs will also be included. If the analyses are done by the monitoring agency or another government agency, then the capital equipment costs need not be included, since costs will exist regardless of the analyses made. For this project, a price list from a private laboratory was used to estimate the laboratory costs (see Table D.2).

REFERENCE

D1. "Model Water Monitoring Program", Environmental Protection Agency, Office of Water Enforcement, 1974.

Table D.2 LABORATORY COSTS

Analysis	Cost	Analysis	Cost
Aluminum	$ 8.50	Iron	$ 7.50
Ammonia	10.00	Lead	7.50
BOD_5	20.00	Manganese	7.50
Carbon	10.00	Mercury	15.00
COD	10.00	Nickel	7.50
Chloride	5.00	Nitrogen	10.00
Chloroform Extract	15.00	Oil-Grease	10.00
Chromium	7.50	pH	3.00
Coliforms-Total	15.00	Phenol	12.50
Coliforms-Fecal	15.00	Phosphorus	10.00
Copper	7.50	Dissolved Solids	10.00
Cyanide	15.00	Suspended Solids	5.00
Dissolved Oxygen	3.00	Tin	8.50
Fluoride	8.00	Zinc	7.50

APPENDIX E

BAYESIAN UPDATE FORMULA

Consider the case when both parameters of an independent normal process are estimated. Using the Bayesian approach, the parameters of the process, the mean μ and precision h, (the precision is equal $1/\sigma^2$ where σ is the standard deviation) are themselves treated as random variables. The most convenient [E1] joint distribution of the parameters - called the natural conjugate prior - is defined by

$$f_{N\gamma}(\mu, h | m, n, v, \nu)$$

$$\propto \exp\left\{-\frac{1}{2}hn(\mu-m)^2\right\} h^{1/2} \qquad \text{(E.1)}$$

$$\times \exp\left\{-\frac{1}{2}\nu v h\right\} h^{\nu/2-1}$$

This distribution is known as the normal-gamma distribution and is uniquely defined by the parameters m,n,v, and ν. m is the estimated mean of the process, v is the estimated variance of the process, n is a constant expressing the confidence (or uncertainty) in the estimated mean, and ν is a constant expressing the confidence in the estimated variance. For the case where the estimated mean, m, and variance, v, were obtained from N identically distributed, independent, normal random variables, $\{x_i\}$, using the sample mean and sample variance, that is

$$m = \frac{1}{N}\sum_{i=1}^{N} x_i$$

and

$$v = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - m)^2 \tag{E.2}$$

then n is equal N and ν is equal N-1. Thus n and ν express the degrees of freedom used to obtain the estimates m and v.

Suppose that estimates of the mean and variance, m and v, of a random process are available with confidence parameters n and ν respectively. The prior distribution is normal-gamma with parameters (m,n,v,ν). If a new sample from the random process is made (independent from the process which yielded m and v) yielding a sufficient statistic (m', n', v', ν'), then the posterior distribution is again normal-gamma with parameters [E1]

$$m'' = \frac{n'm' + nm}{n' + n} \tag{E.3a}$$

$$n'' = n' + n \tag{E.3b}$$

$$v'' = \frac{[\nu'v' + n'm'^2] + [\nu v + nm^2] - (n' + n)m''^2}{\nu' + \nu + 1} \tag{E.3c}$$

$$\nu'' = \nu' + \nu + 1 \tag{E.3d}$$

m" and v" are Bayesian posterior estimates of the mean and the variance and n" and ν'' are the corresponding confidence parameters. The formulas in (E.3) describe how to update old estimates (m,n,v,ν) as new estimates (m', n', v', ν') become available. If the new estimates are from a single data point z, then $m' = z$, $n' = 1$ and $v' = \nu' = 0$.

REFERENCE

E1. Raiffa, H. and Schlaiffer, R., Applied Statistical Decision Theory, The M.I.T. Press, Cambridge, Mass., 1961.

APPENDIX F

ESTIMATION OF THE BOD-DO AND COD-DO TRANSFER COEFFICIENTS AND THE SATURATION LEVEL OF DO*

On streams, rivers, and vertically well-mixed reservoirs the maximum dissolved oxygen deficit ($D_{i,BOD}$) due to a BOD effluent is related to the BOD stream concentration at the effluent source ($CO_{i,BOD}$), the BOD decay rate (K_d), the stream reaeration rate (K_a), and the waste dispersion rate. The initial BOD stream concentration is given by

$$CO_{i,BOD} = \frac{M_{i,BOD} + CU_{i,BOD}\ QU_i}{QU_i + QS_i} \qquad (F.1)$$

The relationship between $D_{i,BOD}$ and $C_{i,BOD}$ can be estimated using a transfer coefficient as

$$D_{i,BOD} = (K_{BOD-DO})\ (CO_{i,BOD}) \qquad (F.2)$$

K_{BOD-CO} can be obtained using Figure F.1 along with Figure F.2. Figure F.1 shows that in streams, K_{BOD-DO} varies primarily with K_a/K_d. Also, as rivers become more tidally influenced and broad, K_{BOD-DO} increases. Values of K_a/K_d can be found for various applications using Figure F.2.

The damage due to COD loadings is difficult to quantify since there are many different kinds of chemicals, each with their own reaction

---

*Information derived from Simplified Mathematical Modeling of Water Quality [F1]

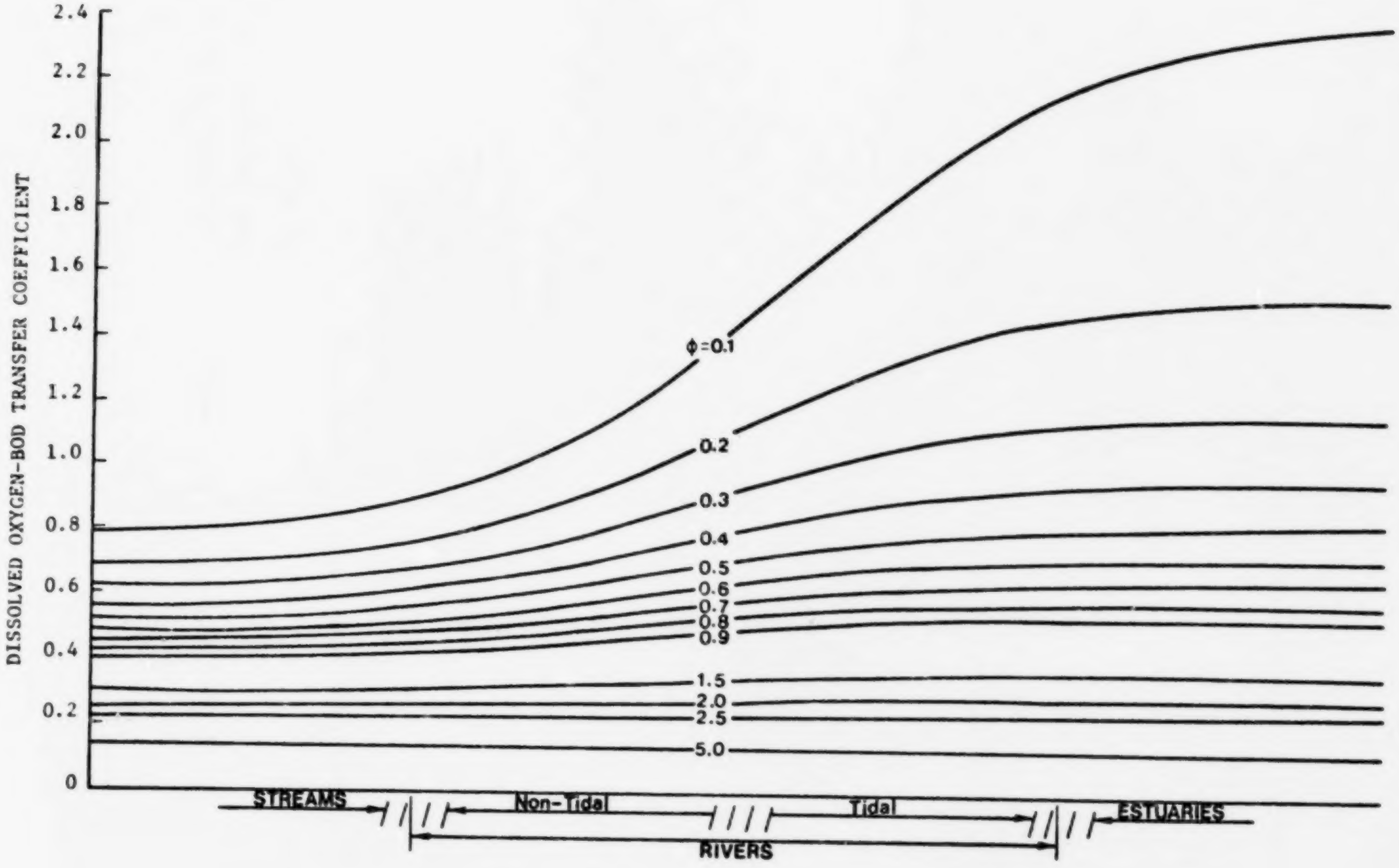

Figure F.1 Dissolved oxygen response as a function of water body type and ϕ. (Note: $\phi = K_a/K_d$)

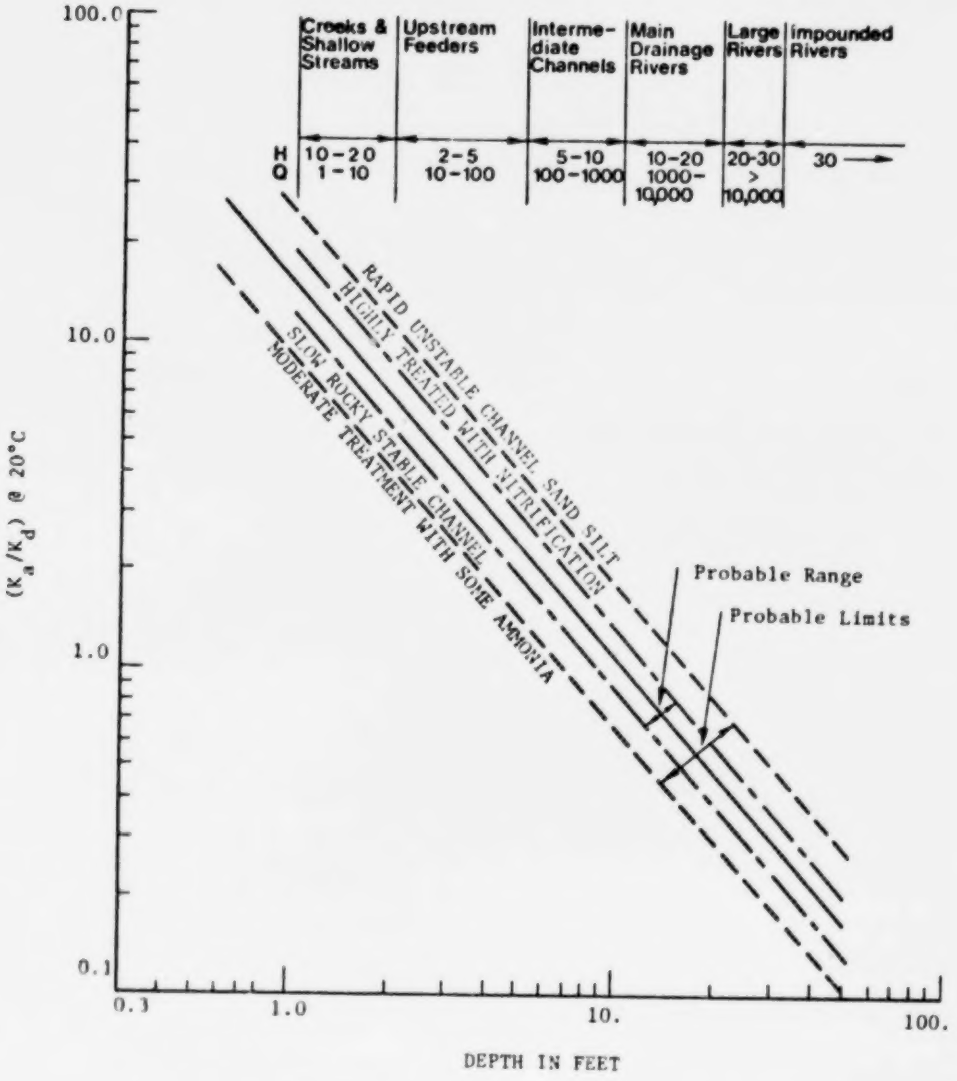

Figure F.2 (K_a/K_d) as a function of depth.

characteristics, which may demand oxygen. Furthermore, the lab tests for COD are performed by heating the sample, which probably would not indicate actual stream damages. For these reasons COD is generally not a modeled constituent and little is known about its stream characteristics. However, Prati et al. [F2] found that the damages due to COD are proportional to those from an equivalent concentration of BOD. The maximum DO uptake due to COD is related to the initial stream COD concentration (C_o) through a transfer function (K_{COD-DO}), which can be estimated as

$$K_{COD-DO} \doteq 0.15\ (K_{BOD-DO}). \tag{F.3}$$

Therefore the COD transfer coefficient can be estimated using Figures F.1 and F.2 along with equation (F.3).

DOSAT, the saturation level of dissolved oxygen in the stream, can be found for various temperatures and salinities using Figure F.3.

REFERENCES

F1. Hydroscience, Inc., Simplified Mathematical Modeling of Water Quality, Environmental Protection Agency, Washington, D.C., March 1971.

F2. Prati, L., et al., "Assessment of Surface Water Quality by a Single Index of Pollution", Water Research (GB), Vol. 5, pp. 741-751, 1971.

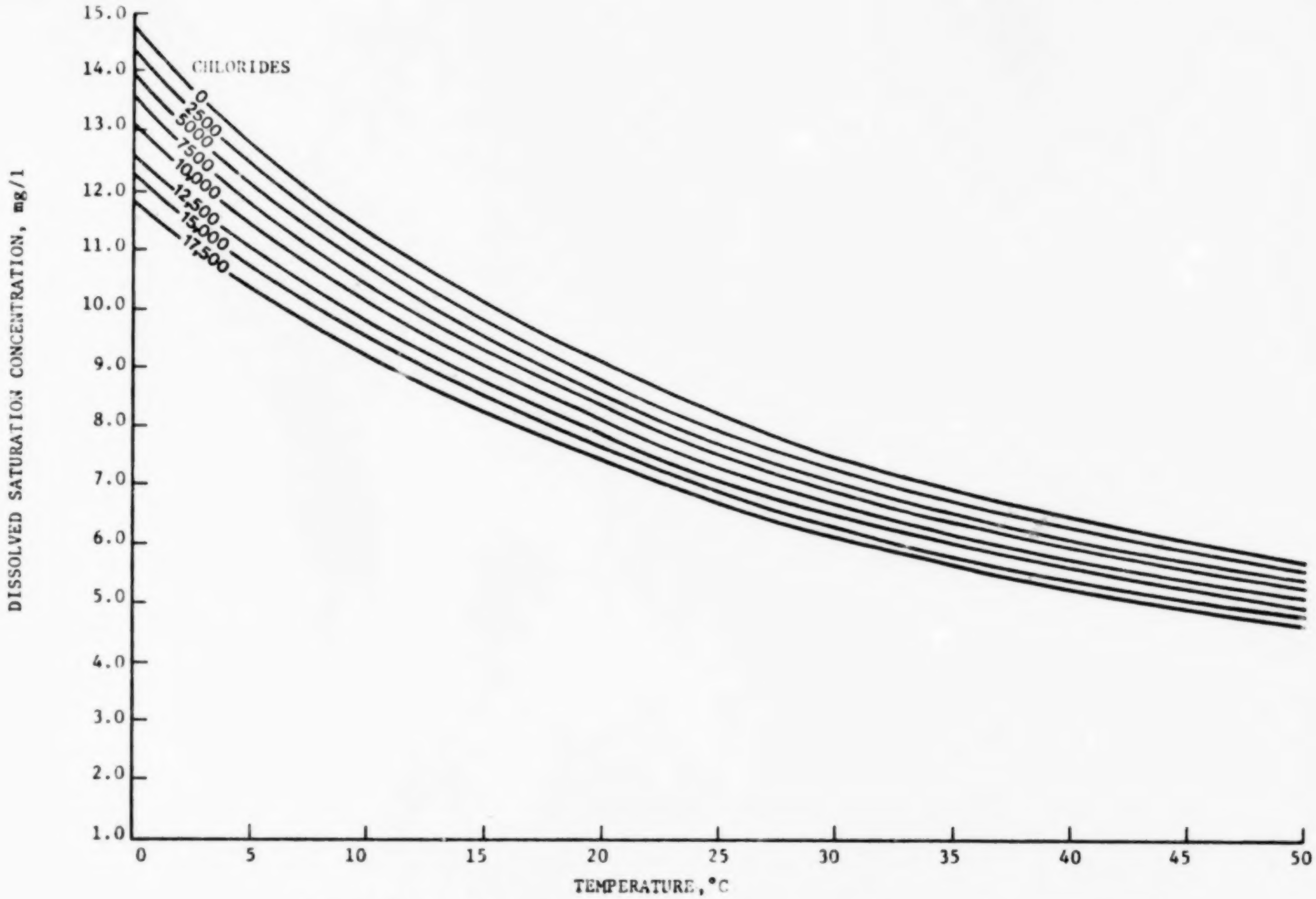

Figure F.3 Dissolved oxygen saturation versus temperature and chlorides.

APPENDIX G

DATA FOR DEMONSTRATION PROJECT

This appendix contains the statistical description, expected damage and probability of no violation for each constituent of each source for Case I and Case II of the demonstration project. The following notation is used:

DIST - Distribution
N - Normal
L - Lognormal
EST. MEAN - Estimated Mean
EST. SIGMA - Estimated Standard Deviation

The units for the standards for the various constituents are in kilograms, except for pH where the units are in pH. The units for estimated mean and estimated standard deviations are in kilograms, if the distribution is normal, and log kilograms if the distribution is lognormal (recall, in the lognormal case, the mean and standard deviation are of the logs of the data). For pH the units are in pH.

In the case of pH-max and pH-min only one value of expected damage and probability of violation is given since only one value is calculated (see Appendix C). Also note that the expected damage only appears once for each constituent of a source for the cases where there are two or more pipes from the source flowing into the stream.

G.1 DATA FOR CASE I

```
                                             ***********
                                              SOURCE  1
                                             ***********
PIPE= 1          MEAN DISCHARGE (ML/DAY)=         .3407          UPSTREAM FLOW (ML/DAY)=      4.8937

     CONSTITUENT             STANDARD     DIST     EST. MEAN       EST. SIGMA    EXPECTED    PROB. OF NO
                                                                                  DAMAGE      VIOLATION
--------------------       ------------   ----    ------------    ------------   --------    -----------
PH-MAX                           9.5000    N            7.5895           .6730   ********    ***********
PH-MIN                           6.5000    N            7.5895           .4395      .2860          .9911
CHROMIUM                          .5299    L           -1.9113           .8876      .8077          .9673
NICKEL                           2.6497    L           -1.4006           .6635     1.3251          .9970
CHLOROFORM EXTRACT               3.9746    L           -1.7580          1.6513     1.8245          .9233


PIPE= 2          MEAN DISCHARGE (ML/DAY)=         .0151          UPSTREAM FLOW (ML/DAY)=      4.8937

     CONSTITUENT             STANDARD     DIST     EST. MEAN       EST. SIGMA    EXPECTED    PROB. OF NO
                                                                                  DAMAGE      VIOLATION
--------------------       ------------   ----    ------------    ------------   --------    -----------
BOD5                              .1987    N             .1184           .0484     1.2426          .9515
SUSPENDED SOLIDS                  .2650    N             .2010           .0896      .0038          .7626
CHLORIDE                         2.6500    N             .0306           .0044      .0005         1.0000


**********************************************************
 SOURCE EXPECTED DAMAGE                          1.8245
 SOURCE PROBABILITY OF NO VIOLATION               .6404
**********************************************************
```

```
                                               ***********
                                                SOURCE  2
                                               ***********
PIPE= 1         MEAN DISCHARGE (ML/DAY)=        .3779         UPSTREAM FLOW (ML/DAY)=     185.9600

     CONSTITUENT             STANDARD     DIST    EST. MEAN                     EXPECTED    PROB. OF NO
                                                                  EST. SIGMA     DAMAGE      VIOLATION
--------------------      ------------    ----   ------------    ------------   --------    -----------
PHOSPHORUS                       .8025     L         -1.3866            .5414      .0931          .9914
PH-MAX                          9.5000     N          7.1500            .5119   ********    ***********
PH-MIN                          6.5000     N          7.1500            .4994      .0104          .9035
SUSPENDED SOLIDS               24.9476     L           .7711            .3048      .0502          .9890
CHLOROFORM EXTRACT              6.0186     L           .0432            .2269     1.3554          .9994


PIPE= 2         MEAN DISCHARGE (ML/DAY)=        .7621         UPSTREAM FLOW (ML/DAY)=     185.9600

     CONSTITUENT             STANDARD     DIST    EST. MEAN                     EXPECTED    PROB. OF NO
                                                                  EST. SIGMA     DAMAGE      VIOLATION
--------------------      ------------    ----   ------------    ------------   --------    -----------
PHOSPHORUS                       .9388     L          -.2520            .3547   ********          .7367
PH-MAX                          9.5000     N          7.9333            .3064   ********    ***********
PH-MIN                          6.5000     N          7.9200            .2460   ********         1.0000
SUSPENDED SOLIDS               58.9670     L          1.5876            .5508   ********          .6302
CHLOROFORM EXTRACT              7.0407     L           .5393            .2396   ********          .9009


*****************************************************
 SOURCE EXPECTED DAMAGF                     1.3554
 SOURCE PROBABILITY OF NO VIOLATION          .3669
*****************************************************
```

```
                                                  ***********
                                                   SOURCE  3
                                                  ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=        .0750          UPSTREAM FLOW (ML/DAY)=   1891.4000

                                                                                  EXPECTED    PROB. OF NO
     CONSTITUENT             STANDARD      DIST    EST. MEAN       EST. SIGMA      DAMAGE      VIOLATION
--------------------      ------------     ----   ------------    ------------   --------    -----------
PH-MAX                          9.5000       N          7.7258           .7820   ********    ***********
PH-MIN                          6.5000       N          7.7258           .5798      .0005          .9711
SUSPENDED SOLIDS               16.0875       N           .5263           .4465      .0000         1.0000
PHOSPHORUS                      3.2175       N           .0477           .0704      .0006         1.0000


****************************************************
 SOURCE EXPECTED DAMAGE                       .0006
 SOURCE PROBABILITY OF NO VIOLATION           .9711
****************************************************
```

```
                                        ***********
                                         SOURCE  4
                                        ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=       .8026          UPSTREAM FLOW (ML/DAY)=    51.3840

                                                                              EXPECTED   PROB. OF NO
     CONSTITUENT            STANDARD     DIST   EST. MEAN      EST. SIGMA      DAMAGE     VIOLATION
--------------------     ------------    ----  ------------   ------------   --------   -----------
PH-MAX                         9.0000     N          8.0385          .1256   ********   ***********
PH-MIN                         6.0000     N          8.0385          .1234      .0451        1.0000
SUSPENDED SOLIDS              18.9265     L           .7329          .1648      .0243         .9995
CHLOROFORM EXTRACT             7.5706     L           .5695          .1684     3.4284         .9670


PIPE= 2          MEAN DISCHARGE (ML/DAY)=       .3762          UPSTREAM FLOW (ML/DAY)=    51.3840

                                                                              EXPECTED   PROB. OF NO
     CONSTITUENT            STANDARD     DIST   EST. MEAN      EST. SIGMA      DAMAGE     VIOLATION
--------------------     ------------    ----  ------------   ------------   --------   -----------
PH-MAX                         9.0000     N          7.9083          .2509   ********   ***********
PH-MIN                         6.0000     N          7.9833          .2342   ********        1.0000
SUSPENDED SOLIDS               7.5705     L           .8516          .2116   ********         .5517
CHLOROFORM EXTRACT             3.0282     L           .2921          .2107   ********         .8153


**************************************************
 SOURCE EXPECTED DAMAGE                    3.4284
 SOURCE PROBABILITY OF NO VIOLATION         .4348
**************************************************
```

```
                                        ***********
                                         SOURCE  6
                                        ***********

PIPE= 1        MEAN DISCHARGE (ML/DAY)=     18.7919            UPSTREAM FLOW (ML/DAY)=  1358.0000

                                                                             EXPECTED   PROB. OF NO
    CONSTITUENT              STANDARD     DIST     EST. MEAN      EST. SIGMA   DAMAGE     VIOLATION
--------------------      ------------    ----   ------------   ------------  --------   -----------
PH-MAX                         10.3000     N           7.6797          .4289  ********   ***********
PH-MIN                          5.8000     N           7.6797          .3663     .0418        1.0000
OIL-GREASE                    251.8800     N         140.9278       128.6569    4.0479        1.0000
PHENOL                           .9072     L           -.9000          .3921    1.4198         .9904


PIPE= 2        MEAN DISCHARGE (ML/DAY)=     34.2089            UPSTREAM FLOW (ML/DAY)=  1358.0000

                                                                             EXPECTED   PROB. OF NO
    CONSTITUENT              STANDARD     DIST     EST. MEAN      EST. SIGMA   DAMAGE     VIOLATION
--------------------      ------------    ----   ------------   ------------  --------   -----------
PH-MAX                         10.3000     N           7.8392          .2907  ********   ***********
PH-MIN                          5.8000     N           7.8392          .3918  ********        1.0000
OIL-GREASE                    459.2050     N         165.8726        68.0088  ********        1.0000
PHENOL                          1.3608     L           -.6423          .3921  ********         .9762


*****************************************************
 SOURCE EXPECTED DAMAGE                       4.0479
 SOURCE PROBABILITY OF NO VIOLATION            .9668
*****************************************************
```

```
                                                  ***********
                                                  SOURCE  7
                                                  ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=      2.8958           UPSTREAM FLOW (ML/DAY)=     28.3890

     CONSTITUENT               STANDARD     DIST    EST. MEAN      EST. SIGMA    EXPECTED    PROR. OF NO
--------------------         -------------  ----  ------------    ------------    DAMAGE      VIOLATION
                                                                                 --------    -----------
PH-MAX                              9.5000    N          6.9933           .4946  ********    ***********
PH-MIN                              6.5000    N          6.9933           .6821     .2903          .7652
SUSPENDED SOLIDS                   42.5835    N         12.5510          6.6731     .0401         1.0000
PHOSPHORUS                          5.6778    N          1.4573           .4256     .9342         1.0000
FLUORIDE                            2.8389    N          5.6674          4.9540     .0004          .2840
COPPER                              1.4194    N           .2221           .1116     .7131         1.0000
LEAD                                 .8517    L         -.0866           .4972    3.5172          .5136


*****************************************************
 SOURCE EXPECTED DAMAGE                       3.5172
 SOURCE PROBABILITY OF NO VIOLATION            .1116
*****************************************************



                                                  ***********
                                                  SOURCE  8
                                                  ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=      .0005            UPSTREAM FLOW (ML/DAY)=    195.7400

     CONSTITUENT               STANDARD     DIST    EST. MEAN      EST. SIGMA    EXPECTED    PROR. OF NO
--------------------         -------------  ----  ------------    ------------    DAMAGE      VIOLATION
                                                                                 --------    -----------
PH-MAX                              9.5000    N          8.6090           .4199  ********    ***********
PH-MIN                              6.5000    N          8.6090           .5094     .0001          .9831
SUSPENDED SOLIDS                   15.8982    N          3.7636          2.3490     .0020         1.0000
PHOSPHORUS                          1.0599    L         -1.7588           .4756     .0032          .9999
CYANIDE                              .1325    L         -1.2287           .1800     .1099          .7697
FLUORIDE                            9.5389    N         15.6843          6.3081     .0000          .1650
CHROMIUM                             .2650    L          -.8677           .5863     .1679          .6901
COPPER                               .5299    L         -1.1041           .6289     .1108          .9061
LEAD                                 .0530    L          -.2816           .7189    1.4083          .0833
CHLOROFORM EXTRACT                  7.9491    N           .2653           .2743     .0740         1.0000


*****************************************************
 SOURCE EXPECTED DAMAGE                       1.4083
 SOURCE PROBABILITY OF NO VIOLATION            .0065
*****************************************************
```

```
                                        ***********
                                         SOURCE  9
                                        ***********

PIPE= 1        MEAN DISCHARGE (ML/DAY)=      5.5546          UPSTREAM FLOW (ML/DAY)=     78.2990

    CONSTITUENT              STANDARD     DIST    EST. MEAN      EST. SIGMA    EXPECTED    PROB. OF NO
                                                                                DAMAGE      VIOLATION
--------------------       ------------   ----   ------------   ------------   --------   -----------
BOD5                           189.2700     N        435.3778       390.7530     4.6630         .2644
PH-MAX                           9.5000     N          8.1921         1.0480   ********   ***********
PH-MIN                           6.5000     N          8.1921          .9570     1.2080         .8555
SUSPENDED SOLIDS               473.1750     L          1.3117          .2691      .0296        1.0000
CHROMIUM                         5.6781     L          1.0355         1.0919     3.9607         .3984
NICKEL                           5.6781     L         -1.8792         1.0136      .2167         .9953
CHLOROFORM EXTRACT             283.9050     N         43.5777        33.3680     7.7820        1.0000


**************************************************
 SOURCE EXPECTED DAMAGE                   7.7820
 SOURCE PROBABILITY OF NO VIOLATION        .0897
**************************************************



                                        ***********
                                         SOURCE 10
                                        ***********

PIPE= 1        MEAN DISCHARGE (ML/DAY)=      1.2848          UPSTREAM FLOW (ML/DAY)=    112.5600

    CONSTITUENT              STANDARD     DIST    EST. MEAN      EST. SIGMA    EXPECTED    PROB. OF NO
                                                                                DAMAGE      VIOLATION
--------------------       ------------   ----   ------------   ------------   --------   -----------
PH-MAX                          10.5000     N          8.1882          .5817   ********   ***********
PH-MIN                           6.5000     N          8.1882          .5614      .1738         .9986
SUSPENDED SOLIDS                46.3715     L          1.3935          .2522      .0257         .8603
PHOSPHORUS                       1.3249     L           .1619          .2897      .3185         .4455
CHLOROFORM EXTRACT              19.8735     L          1.2220          .2599     4.4897         .6154
OIL-GREASE                      19.8735     L          1.4298          .2113     4.0391         .3064


**************************************************
 SOURCE EXPECTED DAMAGE                   4.4897
 SOURCE PROBABILITY OF NO VIOLATION        .0722
**************************************************
```

```
                                   ************
                                    SOURCE 11
                                   ************

PIPE= 1        MEAN DISCHARGE (ML/DAY)=     2.6909         UPSTREAM FLOW (ML/DAY)=     26.1180

     CONSTITUENT            STANDARD     DIST    EST. MEAN      EST. SIGMA    EXPECTED    PROB. OF NO
                                                                               DAMAGE      VIOLATION
--------------------     -------------   ----   ------------   ------------   --------   -----------
PH-MAX                         10.5000     N          8.1815          .6907   ********   ***********
PH-MIN                          6.5000     N          8.1815          .6776      .9760         .9931
CYANIDE                          .6530     L          -.9411          .3946     1.1464         .9723
CHROMIUM                        5.2238     L         -1.0685          .3222      .3893        1.0000
COPPER                          2.6119     L           .1026          .3071     2.7195         .8470
NICKEL                         13.0595     L          -.2420          .5054     1.8169         .9964


**************************************************
 SOURCE EXPECTED DAMAGE                   2.7195
 SOURCE PROBABILITY OF NO VIOLATION        .8149
**************************************************




                                   ************
                                    SOURCE 12
                                   ************

PIPE= 1        MEAN DISCHARGE (ML/DAY)=     4.9209         UPSTREAM FLOW (ML/DAY)=    183.5200

     CONSTITUENT            STANDARD     DIST    EST. MEAN      EST. SIGMA    EXPECTED    PROB. OF NO
                                                                               DAMAGE      VIOLATION
--------------------     -------------   ----   ------------   ------------   --------   -----------
BODS                           41.6380     N         60.5332        52.8607      .8089         .3606
PH-MAX                          9.0000     N          7.5779          .2888   ********   ***********
PH-MIN                          6.0000     N          7.5779          .2910      .0452        1.0000
SUSPENDED SOLIDS              104.0950     L          1.5587          .4165      .0304         .8646
CHLOROFORM EXTRACT             41.6380     N         61.0981       140.8109     5.6605         .4450


**************************************************
 SOURCE EXPECTED DAMAGE                   5.6605
 SOURCE PROBABILITY OF NO VIOLATION        .1387
**************************************************
```

```
                                        ***********
                                         SOURCE 13
                                        ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=       .4444          UPSTREAM FLOW (ML/DAY)=       2.4468

     CONSTITUENT               STANDARD     DIST    EST. MEAN        EST. SIGMA     EXPECTED    PROB. OF NO
                                                                                     DAMAGE      VIOLATION
--------------------        -------------   ----   ------------     ------------    --------    -----------
BOD5                               4.8830     N          2.4000           1.7550      3.3402          .9214
PH=MAX                            10.5000     N          7.8927            .3508    ********    ***********
PH=MIN                             6.0000     N          7.8927            .2699       .6080         1.0000


***************************************************
 SOURCE EXPECTED DAMAGE                   3.3402
 SOURCE PROBABILITY OF NO VIOLATION        .9214
***************************************************



                                        ***********
                                         SOURCE 14
                                        ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=       .1514          UPSTREAM FLOW (ML/DAY)=      19.5750

     CONSTITUENT               STANDARD     DIST    EST. MEAN        EST. SIGMA     EXPECTED    PROB. OF NO
                                                                                     DAMAGE      VIOLATION
--------------------        -------------   ----   ------------     ------------    --------    -----------
PH=MAX                             9.5000     N          7.8002            .4945    ********    ***********
PH=MIN                             6.5000     N          7.8002            .4487       .0398          .9978
SUSPENDED SOLIDS                  50.3440     N          2.4662           1.4728       .0126         1.0000
CYANIDE                             .3596     N           .0140            .0241       .1842         1.0000
CHROMIUM                           4.3152     L         -2.2696           1.5801       .6237          .9670
COPPER                             2.8768     L         -1.0677            .2796       .5301         1.0000
CHLOROFORM EXTRACT                21.5760     N          1.3941            .7672      2.4330         1.0000


***************************************************
 SOURCE EXPECTED DAMAGE                   2.4330
 SOURCE PROBABILITY OF NO VIOLATION        .9649
***************************************************
```

```
                                             ***********
                                              SOURCE 15
                                             ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=        .9024        UPSTREAM FLOW (ML/DAY)=       66.0650

    CONSTITUENT              STANDARD     DIST    EST. MEAN       EST. SIGMA    EXPECTED    PROB. OF NO
                                                                                  DAMAGE      VIOLATION
--------------------      ------------    ----   ------------    ------------   --------    -----------
PH-MAX                          9.0000     N          7.3853          1.4451    ********    ***********
PH-MIN                          6.0000     N          7.3853          1.7557       .7313          .6530
LEAD                             .0084     L          -.0163           .5497      2.8134          .0001


***************************************************
 SOURCE EXPECTED DAMAGE                     2.8134
 SOURCE PROBABILITY OF NO VIOLATION          .0001
***************************************************



                                             ***********
                                              SOURCE 16
                                             ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=        .7253        UPSTREAM FLOW (ML/DAY)=        6.9649

    CONSTITUENT              STANDARD     DIST    EST. MEAN       EST. SIGMA    EXPECTED    PROB. OF NO
                                                                                  DAMAGE      VIOLATION
--------------------      ------------    ----   ------------    ------------   --------    -----------
PH-MAX                          9.5000     N          7.9391           .1695    ********    ***********
PH-MIN                          6.5000     N          7.9391           .1738       .3645         1.0000
SUSPENDED SOLIDS               24.3771     N          4.8520          2.6631       .0636         1.0000
OIL-GREASE                     10.4473     N          4.9186          2.6288      4.0721          .9823
MERCURY                          .0035     L         -3.1565           .2107       .2040          .9995


***************************************************
 SOURCE EXPECTED DAMAGE                     4.0721
 SOURCE PROBABILITY OF NO VIOLATION          .9818
***************************************************
```

```
                                           ***********
                                            SOURCE 17
                                           ***********

PIPE= 1        MEAN DISCHARGE (ML/DAY)=        1.8632        UPSTREAM FLOW (ML/DAY)=    293.6200

                                                                         EXPECTED   PROB. OF NO
    CONSTITUENT           STANDARD    DIST    EST. MEAN      EST. SIGMA    DAMAGE     VIOLATION
--------------------   -------------  ----  ------------   ------------  --------   -----------
CHLOROFORM EXTRACT           40.1240   L           .8641          .5312   4.0183          .9180


PIPE= 2        MEAN DISCHARGE (ML/DAY)=         .4707        UPSTREAM FLOW (ML/DAY)=    293.6200

                                                                         EXPECTED   PROB. OF NO
    CONSTITUENT           STANDARD    DIST    EST. MEAN      EST. SIGMA    DAMAGE     VIOLATION
--------------------   -------------  ----  ------------   ------------  --------   -----------
CHLOROFORM EXTRACT            9.3118   L           .3052          .3105  ********         .9837


PIPE= 3        MEAN DISCHARGE (ML/DAY)=         .6279        UPSTREAM FLOW (ML/DAY)=    293.6200

                                                                         EXPECTED   PROB. OF NO
    CONSTITUENT           STANDARD    DIST    EST. MEAN      EST. SIGMA    DAMAGE     VIOLATION
--------------------   -------------  ----  ------------   ------------  --------   -----------
CHLOROFORM EXTRACT           10.3718   L           .1147          .4631  ********         .9742


PIPE= 4        MEAN DISCHARGE (ML/DAY)=         .0035        UPSTREAM FLOW (ML/DAY)=    293.6200

                                                                         EXPECTED   PROB. OF NO
    CONSTITUENT           STANDARD    DIST    EST. MEAN      EST. SIGMA    DAMAGE     VIOLATION
--------------------   -------------  ----  ------------   ------------  --------   -----------
PH-MAX                        9.5000   N          6.8343          .7875  ********   ***********
PH-MIN                        6.5000   N          6.8343          .9770    .1516          .6335
SUSPENDED SOLIDS            156.7100   L          1.0723          .5123    .0080          .9858
PHOSPHORUS                   31.3420   N         25.6556        14.5367   1.7431          .6522
ALUMINUM                     62.6840   N          2.0438         1.2657   1.3103         1.0000
CHLOROFORM EXTRACT           62.6840   L          1.1427          .5517  ********         .8822


*****************************************************
 SOURCE EXPECTED DAMAGE                       4.0183
 SOURCE PROBABILITY OF NO VIOLATION            .3161
*****************************************************
```

```
                                                  ************
                                                   SOURCE 18
                                                  ************
PIPE= 1         MEAN DISCHARGE (ML/DAY)=     35.5519          UPSTREAM FLOW (ML/DAY)=    132.1300

    CONSTITUENT                   STANDARD      DIST    EST. MEAN       EST. SIGMA     EXPECTED    PROB. OF NO
--------------------            ------------    ----   ------------    ------------     DAMAGE      VIOLATION
                                                                                       --------    -----------
BOD5                               3000.0000     N       38032.0937      37557.3949     8.9420          .1755
SUSPENDED SOLIDS                   4445.2015     N       69360.8340      76030.0332     7.3710          .1966
AMMONIA                             272.1552     N          54.6614         61.2355     3.3255          .9998
DISSOLVED SOLIDS                 213188.2383     N      126617.5869      38748.3101     4.9732          .9873


***************************************************
 SOURCE EXPECTED DAMAGE                      8.9420
 SOURCE PROBABILITY OF NO VIOLATION           .0341
***************************************************




                                                  ************
                                                   SOURCE 19
                                                  ************
PIPE= 1         MEAN DISCHARGE (ML/DAY)=       .1330          UPSTREAM FLOW (ML/DAY)=      4.8937

    CONSTITUENT                   STANDARD      DIST    EST. MEAN       EST. SIGMA     EXPECTED    PROB. OF NO
--------------------            ------------    ----   ------------    ------------     DAMAGE      VIOLATION
                                                                                       --------    -----------
SUSPENDED SOLIDS                    123.0225     L            .4533          1.8676     1.5105          .8096
CHLOROFORM EXTRACT                   73.8135     L            .0076           .5512     5.7877          .9996


***************************************************
 SOURCE EXPECTED DAMAGE                      5.7877
 SOURCE PROBABILITY OF NO VIOLATION           .8093
***************************************************
```

```
                                             ***********
                                              SOURCE 20
                                             ***********

PIPE= 1         MEAN DISCHARGE (ML/DAY)=        .8176          UPSTREAM FLOW (ML/DAY)=    195.7500

                                                                              EXPECTED   PROB. OF NO
     CONSTITUENT           STANDARD     DIST    EST. MEAN       EST. SIGMA     DAMAGE     VIOLATION
--------------------     -------------  ----   ------------   ------------   --------   -----------
PH-MAX                          9.5000    N          6.7000          .3809   ********   ***********
PH-MIN                          6.5000    N          6.7000          .2437      .0073         .7941
SUSPENDED SOLIDS               49.8725    N         28.1263        16.3831      .0145         .9078
PHOSPHORUS                      9.9745    N          3.5321         3.5105      .3888         .9668


*****************************************************
 SOURCE EXPECTED DAMAGE                        .3888
 SOURCE PROBABILITY OF NO VIOLATION            .6969
*****************************************************


                                             ***********
                                              SOURCE 22
                                             ***********

PIPE= 1         MEAN DISCHARGE (ML/DAY)=      40.7535          UPSTREAM FLOW (ML/DAY)=    203.0900
  MEAN DO CONCENTRATION (MG/L)=      4.3879

                                                                              EXPECTED   PROB. OF NO
     CONSTITUENT           STANDARD     DIST    EST. MEAN       EST. SIGMA     DAMAGE     VIOLATION
--------------------     -------------  ----   ------------   ------------   --------   -----------
BOD5                         1360.7760    N       1876.9772      1464.5886     5.9598         .3622
SUSPENDED SOLIDS              907.1840    L          3.1263          .3946      .8111         .3345
PHOSPHORUS                    378.5300    L          2.0386          .2929     5.4719         .9673


*****************************************************
 SOURCE EXPECTED DAMAGE                       5.9598
 SOURCE PROBABILITY OF NO VIOLATION            .1172
*****************************************************
```

```
                                                   ************
                                                    SOURCE 23
                                                   ************
PIPE= 1         MEAN DISCHARGE (ML/DAY)=        .4251          UPSTREAM FLOW (ML/DAY)=     14.9260

    CONSTITUENT               STANDARD      DIST   EST. MEAN     EST. SIGMA   EXPECTED   PROB. OF NO
--------------------        -------------   ----  ------------  ------------   DAMAGE     VIOLATION
BOD5                             184.1583    N        39.9745       17.9516   --------   -----------
SUSPENDED SOLIDS                 104.7798    N        30.4148       28.3043     2.8746        1.0000
PHOSPHORUS                         4.3152    N         3.7928         .8987      .2114         .9957
                                                                                4.2206         .7195

*************************************************
SOURCE EXPECTED DAMAGE                      4.2206
SOURCE PROBABILITY OF NO VIOLATION           .7164
*************************************************
```

```
                                                   ************
                                                    SOURCE 24
                                                   ************
PIPE= 1         MEAN DISCHARGE (ML/DAY)=       3.0492          UPSTREAM FLOW (ML/DAY)=    269.1600

    CONSTITUENT               STANDARD      DIST   EST. MEAN     EST. SIGMA   EXPECTED   PROB. OF NO
--------------------        -------------   ----  ------------  ------------   DAMAGE     VIOLATION
BOD5                             408.2328    N       244.2449       67.0962   --------   -----------
SUSPENDED SOLIDS                 272.1552    N       146.0120       37.1962     1.0989         .9927
                                                                                 .0536         .9997

*************************************************
SOURCE EXPECTED DAMAGE                      1.0989
SOURCE PROBABILITY OF NO VIOLATION           .9924
*************************************************
```

```
                                                  ***********
                                                  SOURCE 25
                                                  ***********
PIPE= 1          MEAN DISCHARGE (ML/DAY)=     164.9721          UPSTREAM FLOW (ML/DAY)=   1827.8000

    CONSTITUENT                STANDARD     DIST   EST. MEAN     EST. SIGMA   EXPECTED   PROB. OF NO
--------------------        -------------   ----  ------------  ------------   DAMAGE     VIOLATION
BOD5                            4535.9200     N      5622.2911     2494.1224   --------  -----------
SUSPENDED SOLIDS                3428.7360     L         3.7498         .1844     3.7470        .3316
                                                                                   .3084        .1518

**************************************************
SOURCE EXPECTED DAMAGE                /     3.7470
SOURCF PROBABILITY OF NO VIOLATION           .0503
**************************************************




                                                  ***********
                                                  SOURCE 26
                                                  ***********
PIPE= 1          MEAN DISCHARGE (ML/DAY)=       7.1535          UPSTREAM FLOW (ML/DAY)=   1862.1000
  MEAN DO CONCENTRATION (MG/L)=        5.7838

    CONSTITUENT                STANDARD     DIST   EST. MEAN     EST. SIGMA   EXPECTED   PROB. OF NO
--------------------        -------------   ----  ------------  ------------   DAMAGE     VIOLATION
BOD5                             278.9591     L         2.0125         .4327   --------  -----------
SUSPENDED SOLIDS                 302.0923     L         2.2752         .3726      .1150        .8416
PHOSPHORUS                        72.2990     N        43.2767       74.5506      .0146        .7088
                                                                                   .6019        .6515

**************************************************
SOURCE EXPECTED DAMAGE                       .6019
SOURCE PROBABILITY OF NO VIOLATION           .3886
**************************************************
```

```
                                                        ***********
                                                         SOURCE 27
                                                        ***********
PIPE= 1          MEAN DISCHARGE (ML/DAY)=        5.5699          UPSTREAM FLOW (ML/DAY)=    349.9000

     CONSTITUENT                    STANDARD      DIST    EST. MEAN      EST. SIGMA     EXPECTED    PROB. OF NO
--------------------             -------------    ----  ------------   ------------     DAMAGE      VIOLATION
BOD5                                  272.1552      N      3543.7104      1179.1592     --------    -----------
SUSPENDED SOLIDS                      272.1552      N      2791.1689      1131.8056       6.4625          .0028
PHOSPHORUS                             58.2940      N       291.9943        61.2851        .7859          .0130
                                                                                          6.5742          .0001

**************************************************
SOURCE EXPECTED DAMAGE
SOURCE PROBABILITY OF NO VIOLATION          6.5742
                                             .0000
**************************************************
```

```
                                                        ***********
                                                         SOURCE 28
                                                        ***********
PIPE= 1          MEAN DISCHARGE (ML/DAY)=        110.8503
  MEAN DO CONCENTRATION (MG/L)=       4.8750                   UPSTREAM FLOW (ML/DAY)=    266.7100

     CONSTITUENT                    STANDARD      DIST    EST. MEAN      EST. SIGMA     EXPECTED    PROB. OF NO
--------------------             -------------    ----  ------------   ------------     DAMAGE      VIOLATION
BOD5                                 4989.5120      N      1228.5462      1460.4089     --------    -----------
SUSPENDED SOLIDS                     4082.3280      N      2549.2877      2072.4836       4.5018          .9950
PHOSPHORUS                            529.9500      N       333.7107       177.2988        .7041          .7703
                                                                                          6.3182          .8658

**************************************************
SOURCE EXPECTED DAMAGE
SOURCE PROBABILITY OF NO VIOLATION          6.3182
                                             .6636
**************************************************
```

```
                                                  ************
                                                   SOURCE 29
                                                  ************

PIPE= 1         MEAN DISCHARGE (ML/DAY)=       4.1106          UPSTREAM FLOW (ML/DAY)=     12.2340

                                                                                EXPECTED   PROB. OF NO
    CONSTITUENT              STANDARD     DIST     EST. MEAN       EST. SIGMA     DAMAGE     VIOLATION
--------------------      -------------   ----    ------------    ------------   --------   -----------
BOD5                           170.0970    N          73.5866         67.2152     6.0919          .9245
SUSPENDED SOLIDS               170.0970    L           1.6048           .3684      .3525          .9553


*****************************************************
 SOURCE EXPECTED DAMAGE                      6.0919
 SOURCE PROBABILITY OF NO VIOLATION           .8832
*****************************************************




                                                  ************
                                                   SOURCE 30
                                                  ************

PIPE= 1         MEAN DISCHARGE (ML/DAY)=      35.0425          UPSTREAM FLOW (ML/DAY)=   1862.1000

                                                                                EXPECTED   PROB. OF NO
    CONSTITUENT              STANDARD     DIST     EST. MEAN       EST. SIGMA     DAMAGE     VIOLATION
--------------------      -------------   ----    ------------    ------------   --------   -----------
BOD5                          1587.5720    N        1437.8229        570.2724     1.0909          .6036
SUSPENDED SOLIDS              1360.7760    N        1460.9078        552.7678      .0770          .4281


*****************************************************
 SOURCE EXPECTED DAMAGE                      1.0909
 SOURCE PROBABILITY OF NO VIOLATION           .2584
*****************************************************
```

```
                                                  ***********
                                                   SOURCE  1
                                                  ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=        .3407          UPSTREAM FLOW (ML/DAY)=      4.8937

     CONSTITUENT               STANDARD    DIST    EST. MEAN       EST. SIGMA   EXPECTED     PROB. OF NO
                                                                                 DAMAGE       VIOLATION
--------------------        -------------  ----  ------------    ------------  --------     -----------
PH-MAX                            9.5000     N         7.5679           .6912  ********     ***********
PH-MIN                            6.5000     N         7.5766           .3141     .2891           .9971
CHROMIUM                           .5299     L        -1.8839           .6766     .6285           .9913
NICKEL                            2.6497     L        -1.5674           .6141    1.1391           .9994
CHLOROFORM EXTRACT                3.9746     L        -1.0848          1.4235    2.7477           .8816


PIPE= 2          MEAN DISCHARGE (ML/DAY)=        .0151          UPSTREAM FLOW (ML/DAY)=      4.8937

     CONSTITUENT               STANDARD    DIST    EST. MEAN       EST. SIGMA   EXPECTED     PROB. OF NO
                                                                                 DAMAGE       VIOLATION
--------------------        -------------  ----  ------------    ------------  --------     -----------
BOD5                               .1987     N          .1371           .0447    1.2462           .9161
SUSPENDED SOLIDS                   .2650     N          .1914           .0646     .0036           .8727
CHLORIDE                          2.6500     N          .0287           .0032     .0004          1.0000


**************************************************
 SOURCE EXPECTED DAMAGE                     2.7477
 SOURCE PROBABILITY OF NO VIOLATION          .6963
**************************************************
```

```
                                                  ************
                                                   SOURCE  2
                                                  ************
PIPE= 1          MEAN DISCHARGE (ML/DAY)=          .3779          UPSTREAM FLOW (ML/DAY)=     185.9600

     CONSTITUENT              STANDARD      DIST    EST. MEAN       EST. SIGMA    EXPECTED    PROB. OF NO
--------------------        ------------    ----  ------------    ------------     DAMAGE      VIOLATION
                                                                                  --------    -----------
PHOSPHORUS                         .8025     L          -.8619           .7768       .1993          .8381
PH-MAX                            9.5000     N          7.1062          1.0055    ********    ***********
PH-MIN                            6.5000     N          7.1062           .6984       .0530          .7987
SUSPENDED SOLIDS                 24.9476     L           .8869           .3668       .0645          .9179
CHLOROFORM EXTRACT                6.0186     L           .1969           .3496      1.7011          .9522


PIPE= 2          MEAN DISCHARGE (ML/DAY)=          .7621          UPSTREAM FLOW (ML/DAY)=     185.9600

     CONSTITUENT              STANDARD      DIST    EST. MEAN       EST. SIGMA    EXPECTED    PROB. OF NO
--------------------        ------------    ----  ------------    ------------     DAMAGE      VIOLATION
                                                                                  --------    -----------
PHOSPHORUS                         .9388     L          -.1358           .4328    ********          .5989
PH-MAX                            9.5000     N          7.8937           .2363    ********    ***********
PH-MIN                            6.5000     N          7.8862           .1998    ********         1.0000
SUSPENDED SOLIDS                 58.9670     L          1.7498           .5023    ********          .5165
CHLOROFORM EXTRACT                7.0407     L           .6289           .2428    ********          .8161


**************************************************
 SOURCE EXPECTED DAMAGE                  1.7011
 SOURCE PROBABILITY OF NO VIOLATION       .1477
**************************************************
```

```
                                                            ************
                                                             SOURCE  3
                                                            ************

PIPE= 1          MEAN DISCHARGE (ML/DAY)=        .0750          UPSTREAM FLOW (ML/DAY)=   1891.4000

     CONSTITUENT              STANDARD     DIST    EST. MEAN       EST. SIGMA   EXPECTED    PROB. OF NO
--------------------       ------------    ----   ------------   ------------    DAMAGE     VIOLATION
                                                                                 --------   -----------
PH-MAX                           9.5000     N          7.7486          .6625     ********   ***********
PH-MIN                           6.5000     N          7.7486          .5844        .0003          .9796
SUSPENDED SOLIDS                16.0875     N           .6242          .6757        .0000         1.0000
PHOSPHORUS                       3.2175     N           .0486          .0661        .0006         1.0000


*****************************************************
 SOURCE EXPECTED DAMAGE                       .0006
 SOURCE PROBABILITY OF NO VIOLATION           .9796
*****************************************************
```

```
                                       ************
                                        SOURCE  4
                                       ************

PIPE= 1         MEAN DISCHARGE (ML/DAY)=       .8026          UPSTREAM FLOW (ML/DAY)=     51.3840

                                                                           EXPECTED    PROB. OF NO
     CONSTITUENT            STANDARD      DIST    EST. MEAN      EST. SIGMA    DAMAGE      VIOLATION
--------------------     -------------    ----   ------------   ------------  --------    -----------
PH-MAX                          9.0000     N          8.0437          .1003   ********    ***********
PH-MIN                          6.0000     N          8.0437          .1087      .0400         1.0000
SUSPENDED SOLIDS               18.9265     L           .6157          .2950      .0222          .9875
CHLOROFORM EXTRACT              7.5706     L           .3023          .5246     3.1067          .8643


PIPE= 2         MEAN DISCHARGE (ML/DAY)=       .3762          UPSTREAM FLOW (ML/DAY)=     51.3840

                                                                           EXPECTED    PROB. OF NO
     CONSTITUENT            STANDARD      DIST    EST. MEAN      EST. SIGMA    DAMAGE      VIOLATION
--------------------     -------------    ----   ------------   ------------  --------    -----------
PH-MAX                          9.0000     N          7.8273          .2418   ********    ***********
PH-MIN                          6.0000     N          7.9273          .2991   ********         1.0000
SUSPENDED SOLIDS                7.5705     L           .6035          .4231   ********          .7426
CHLOROFORM EXTRACT              3.0282     L           .0320          .4540   ********          .8388


************************************************
 SOURCE EXPECTED DAMAGE                  3.1067
 SOURCE PROBABILITY OF NO VIOLATION       .5316
************************************************
```

```
                                                       ***********
                                                        SOURCE  6
                                                       ***********
PIPE= 1          MEAN DISCHARGE (ML/DAY)=     18.7919            UPSTREAM FLOW (ML/DAY)=   1358.0000

     CONSTITUENT            STANDARD      DIST    EST. MEAN                     EXPECTED    PROB. OF NO
--------------------      ------------    ----   ------------    EST. SIGMA      DAMAGE      VIOLATION
PH=MAX                        10.3000       N          7.6891   ------------    --------    -----------
PH=MIN                         5.8000       N          7.6891          .3804    ********    ***********
OIL-GREASE                   251.8800       N         95.7457          .3377       .0378         1.0000
PHENOL                          .9072       L         -.0200        100.3298      3.7626          .9402
                                                                       .6685      3.4322          .4867


PIPE= 2          MEAN DISCHARGE (ML/DAY)=     34.2089            UPSTREAM FLOW (ML/DAY)=   1358.0000

     CONSTITUENT            STANDARD      DIST    EST. MEAN                     EXPECTED    PROB. OF NO
--------------------      ------------    ----   ------------    EST. SIGMA      DAMAGE      VIOLATION
PH=MAX                        10.3000       N          7.7908   ------------    --------    -----------
PH=MIN                         5.8000       N          7.7908          .3885    ********    ***********
OIL-GREASE                   458.2050       N        137.1951          .3283    ********         1.0000
PHENOL                         1.3608       L         -.0998         63.3132    ********         1.0000
                                                                       .5186    ********          .6738


*****************************************************
 SOURCE EXPECTED DAMAGE                       3.7626
 SOURCE PROBABILITY OF NO VIOLATION            .3083
*****************************************************
```

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                                                   ************
                                                    SOURCE  7
                                                   ************

PIPE= 1        MEAN DISCHARGE (ML/DAY)=      2.8958          UPSTREAM FLOW (ML/DAY)=     28.3690

     CONSTITUENT              STANDARD      DIST    EST. MEAN      EST. SIGMA    EXPECTED    PROB. OF NO
                                                                                  DAMAGE      VIOLATION
--------------------      -------------    ----   ------------   ------------   --------    -----------
PH-MAX                          9.5000       N          6.9933          .4946   ********    ***********
PH-MIN                          6.5000       N          6.9933          .6821      .2903           .7652
SUSPENDED SOLIDS               42.5835       N         12.5510         6.6731      .0404          1.0000
PHOSPHORUS                      5.6778       N          1.4573          .4256      .9317          1.0000
FLUORIDE                        2.8389       N          5.6674         4.9540      .0004           .2840
COPPER                          1.4194       N           .2221          .1116      .7131          1.0000
LEAD                             .8517       L          -.0866          .4972     3.5172           .5136


*****************************************************
 SOURCE EXPECTED DAMAGE                      3.5172
 SOURCE PROBABILITY OF NO VIOLATION           .1116
*****************************************************


                                                   ************
                                                    SOURCE  8
                                                   ************

PIPE= 1        MEAN DISCHARGE (ML/DAY)=       .0005          UPSTREAM FLOW (ML/DAY)=    195.7400

     CONSTITUENT              STANDARD      DIST    EST. MEAN      EST. SIGMA    EXPECTED    PROB. OF NO
                                                                                  DAMAGE      VIOLATION
--------------------      -------------    ----   ------------   ------------   --------    -----------
PH-MAX                          9.5000       N          8.6556          .3375   ********    ***********
PH-MIN                          6.5000       N          8.6556          .3978      .0001           .9938
SUSPENDED SOLIDS               15.8982       N          3.6418         2.5472      .0019          1.0000
PHOSPHORUS                      1.0599       L         -1.6940          .4735      .0037           .9999
CYANIDE                          .1325       L         -1.2287          .1800      .0658           .9744
FLUORIDE                        9.5389       N         23.5479        12.2286      .0000           .1260
CHROMIUM                         .2650       L          -.6769          .4964      .2042           .5799
COPPER                           .5299       L          -.7528          .5214      .1812           .8199
LEAD                             .0530       L          -.1176          .4263     1.5139           .0033
CHLOROFORM EXTRACT              7.9491       N           .2652          .2454      .0722          1.0000


*****************************************************
 SOURCE EXPECTED DAMAGE                      1.5139
 SOURCE PROBABILITY OF NO VIOLATION           .0002
*****************************************************
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                                                    ***********
                                                    SOURCE  9
                                                    ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=      5.5546             UPSTREAM FLOW (ML/DAY)=      78.2990

     CONSTITUENT               STANDARD      DIST     EST. MEAN         EST. SIGMA     EXPECTED    PROB. OF NO
                                                                                        DAMAGE      VIOLATION
--------------------        ------------     ----    -----------      ------------     --------    -----------
BOD5                            189.2700      N          426.1681         269.2156       4.6290          .1694
PH-MAX                            9.5000      N            8.9937           1.1545     ********    ***********
PH-MIN                            6.5000      N            8.9937           1.1431       2.7035          .6549
SUSPENDED SOLIDS                473.1750      L            1.2750            .3221        .0296         1.0000
CHROMIUM                          5.6781      L            1.3116            .8830       4.5256          .2639
NICKEL                            5.6781      L           -1.6607            .8699        .2358          .9972
CHLOROFORM EXTRACT              283.9050      N           83.8446          58.0347       8.7244          .9997


**************************************************
 SOURCE EXPECTED DAMAGE                      8.7244
 SOURCE PROBABILITY OF NO VIOLATION           .0326
**************************************************



                                                    ***********
                                                    SOURCE 10
                                                    ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=      1.2848             UPSTREAM FLOW (ML/DAY)=     112.5600

     CONSTITUENT               STANDARD      DIST     EST. MEAN         EST. SIGMA     EXPECTED    PROB. OF NO
                                                                                        DAMAGE      VIOLATION
--------------------        ------------     ----    -----------      ------------     --------    -----------
PH-MAX                           10.5000      N            8.2339            .7128     ********    ***********
PH-MIN                            6.5000      N            8.2339            .8945        .2517          .9730
SUSPENDED SOLIDS                 46.3715      L            1.4912            .2836        .0337          .7314
PHOSPHORUS                        1.3249      L             .0772            .2934        .2637          .5609
CHLOROFORM EXTRACT               19.8735      L            1.3489            .3418       5.6230          .4411
OIL-GREASE                       19.8735      L            1.3559            .3183       3.9552          .0282


**************************************************
 SOURCE EXPECTED DAMAGE                      5.6230
 SOURCE PROBABILITY OF NO VIOLATION           .0754
**************************************************
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                                                  ************
                                                   SOURCE 11
                                                  ************

PIPE= 1         MEAN DISCHARGE (ML/DAY)=      2.6909          UPSTREAM FLOW (ML/DAY)=     26.1180

                                                                               EXPECTED    PROB. OF NO
    CONSTITUENT              STANDARD    DIST    EST. MEAN       EST. SIGMA    DAMAGE      VIOLATION
--------------------      -------------  ----   ------------   ------------   --------    -----------
PH-MAX                          10.5000    N          8.4380          .5413   ********    ***********
PH-MIN                           6.5000    N          8.4630          .6752     1.2346          .9981
CYANIDE                           .6530    L        -1.6157           .5629      .3756          .9945
CHROMIUM                         5.2238    L        -1.2009           .2271      .2506         1.0000
COPPER                           2.6119    L         -.1407           .3479     2.0994          .9455
NICKEL                          13.0595    L         -.5753           .3994     1.5146         1.0000


**************************************************
 SOURCE EXPECTED DAMAGE                     2.0994
 SOURCE PROBABILITY OF NO VIOLATION          .9385
**************************************************



                                                  ************
                                                   SOURCE 12
                                                  ************

PIPE= 1         MEAN DISCHARGE (ML/DAY)=      4.9209          UPSTREAM FLOW (ML/DAY)=    183.5200

                                                                               EXPECTED    PROB. OF NO
    CONSTITUENT              STANDARD    DIST    EST. MEAN       EST. SIGMA    DAMAGE      VIOLATION
--------------------      -------------  ----   ------------   ------------   --------    -----------
BOD5                            41.6380    N         49.8479        41.6894      .7471          .4219
PH-MAX                           9.0000    N          7.4458          .4485   ********    ***********
PH-MIN                           6.0000    N          7.4458          .6880      .0699          .9819
SUSPENDED SOLIDS               104.0950    L          1.4247          .5307      .0298          .8680
CHLOROFORM EXTRACT              41.6380    N         45.7137        80.2100     5.3977          .4797


**************************************************
 SOURCE EXPECTED DAMAGE                     5.3977
 SOURCE PROBABILITY OF NO VIOLATION          .1725
**************************************************
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                                                  ************
                                                   SOURCE 13
                                                  ************

PIPE= 1          MEAN DISCHARGE (ML/DAY)=        .4444          UPSTREAM FLOW (ML/DAY)=      2.4468

                                                                                  EXPECTED    PROB. OF NO
     CONSTITUENT              STANDARD      DIST    EST. MEAN       EST. SIGMA     DAMAGE      VIOLATION
--------------------        ------------    ----   ------------    ------------   --------    -----------
BOD5                              4.8830      N          3.1851          2.5917     3.5355          .7438
PH-MAX                           10.5000      N          7.7968           .2909   ********    ***********
PH-MIN                            6.0000      N          7.7968           .2994      .4554         1.0000


**************************************************
 SOURCE EXPECTED DAMAGE                     3.5355
 SOURCE PROBABILITY OF NO VIOLATION          .7438
**************************************************



                                                  ************
                                                   SOURCE 14
                                                  ************

PIPE= 1          MEAN DISCHARGE (ML/DAY)=        .1514          UPSTREAM FLOW (ML/DAY)=     19.5750

                                                                                  EXPECTED    PROB. OF NO
     CONSTITUENT              STANDARD      DIST    EST. MEAN       EST. SIGMA     DAMAGE      VIOLATION
--------------------        ------------    ----   ------------    ------------   --------    -----------
PH-MAX                            9.5000      N          7.8169           .3460   ********    ***********
PH-MIN                            6.5000      N          7.8169           .3183      .0287         1.0000
SUSPENDED SOLIDS                 50.3440      N          2.4780          1.5581      .0127         1.0000
CYANIDE                            .3596      N           .0177           .0284      .2265         1.0000
CHROMIUM                          4.3152      L         -1.9036          1.0644      .4666          .9915
COPPER                            2.8768      L         -1.0361           .2755      .5661         1.0000
CHLOROFORM EXTRACT               21.5760      N          1.2122           .5944     2.2673         1.0000


**************************************************
 SOURCE EXPECTED DAMAGE                     2.2673
 SOURCE PROBABILITY OF NO VIOLATION          .9914
**************************************************
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                                                  ***********
                                                   SOURCE 15
                                                  ***********

PIPE= 1        MEAN DISCHARGE (ML/DAY)=       .9024          UPSTREAM FLOW (ML/DAY)=     66.0650

    CONSTITUENT               STANDARD     DIST    EST. MEAN       EST. SIGMA     EXPECTED    PROB. OF NO
                                                                                   DAMAGE      VIOLATION
--------------------       -------------   ----   ------------    ------------    --------    -----------
PH=MAX                            9.0000     N          8.4552          1.8041    ********    ***********
PH=MIN                            6.0000     N          8.4552          1.6307      1.5457          .5526
LEAD                               .0084     L          -.2231           .6257      2.3758          .0016


*****************************************************
 SOURCE EXPECTED DAMAGE                       2.3758
 SOURCE PROBABILITY OF NO VIOLATION            .0009
*****************************************************



                                                  ***********
                                                   SOURCE 16
                                                  ***********

PIPE= 1        MEAN DISCHARGE (ML/DAY)=       .7253          UPSTREAM FLOW (ML/DAY)=      6.9649

    CONSTITUENT               STANDARD     DIST    EST. MEAN       EST. SIGMA     EXPECTED    PROB. OF NO
                                                                                   DAMAGE      VIOLATION
--------------------       -------------   ----   ------------    ------------    --------    -----------
PH=MAX                            9.5000     N          7.9801           .2045    ********    ***********
PH=MIN                            6.5000     N          7.9801           .2307       .8128         1.0000
SUSPENDED SOLIDS                 24.3771     N          4.6869          2.8447       .0617         1.0000
OIL=GREASE                       10.4473     N          4.3342          1.9318      4.1203          .9992
MERCURY                            .0035     L         -3.0912           .2410       .2459          .9957


*****************************************************
 SOURCE EXPECTED DAMAGE                       4.1203
 SOURCE PROBABILITY OF NO VIOLATION            .9949
*****************************************************
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                                                  ***********
                                                   SOURCE 17
                                                  ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=        1.8632          UPSTREAM FLOW (ML/DAY)=    293.6200

                                                                              EXPECTED    PROB. OF NO
     CONSTITUENT            STANDARD     DIST    EST. MEAN      EST. SIGMA     DAMAGE      VIOLATION
--------------------     ------------    ----   ------------   ------------   --------    -----------
CHLOROFORM EXTRACT            40.1240     L           1.0787          .3438    3.9864           .9365



PIPE= 2          MEAN DISCHARGE (ML/DAY)=         .4707          UPSTREAM FLOW (ML/DAY)=    293.6200

                                                                              EXPECTED    PROB. OF NO
     CONSTITUENT            STANDARD     DIST    EST. MEAN      EST. SIGMA     DAMAGE      VIOLATION
--------------------     ------------    ----   ------------   ------------   --------    -----------
CHLOROFORM EXTRACT             9.3118     L            .3197          .2984   ********          .9852



PIPE= 3          MEAN DISCHARGE (ML/DAY)=         .6279          UPSTREAM FLOW (ML/DAY)=    293.6200

                                                                              EXPECTED    PROB. OF NO
     CONSTITUENT            STANDARD     DIST    EST. MEAN      EST. SIGMA     DAMAGE      VIOLATION
--------------------     ------------    ----   ------------   ------------   --------    -----------
CHLOROFORM EXTRACT            10.3718     L            .2606          .3847   ********          .9752



PIPE= 4          MEAN DISCHARGE (ML/DAY)=         .0035          UPSTREAM FLOW (ML/DAY)=    293.6200

                                                                              EXPECTED    PROB. OF NO
     CONSTITUENT            STANDARD     DIST    EST. MEAN      EST. SIGMA     DAMAGE      VIOLATION
--------------------     ------------    ----   ------------   ------------   --------    -----------
PH-MAX                         9.5000     N           7.1147          .8449   ********    ***********
PH-MIN                         6.5000     N           7.1147          .6790     .0573           .9150
SUSPENDED SOLIDS             156.7100     L           1.1375          .3960     .0070           .9962
PHOSPHORUS                    31.3420     N          33.4686        23.3815    2.2395           .4638
ALUMINUM                      62.6840     N           1.4133         2.3094    1.0358          1.0000
CHLOROFORM EXTRACT            62.6840     L           1.1260          .4472   ********          .9333



*************************************************
 SOURCE EXPECTED DAMAGE                   3.9864
 SOURCE PROBABILITY OF NO VIOLATION        .3162
*************************************************
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                                          ************
                                           SOURCE 18
                                          ************

PIPE= 1         MEAN DISCHARGE (ML/DAY)=      35.5519          UPSTREAM FLOW (ML/DAY)=     132.1300

                                                                                EXPECTED   PROB. OF NO
     CONSTITUENT             STANDARD    DIST   EST. MEAN      EST. SIGMA        DAMAGE     VIOLATION
-------------------      -------------   ----  ------------   ------------     --------   -----------
BOD5                         3000.0000    N      29419.5886     25906.2375       9.1068         .1539
SUSPENDED SOLIDS             4445.2015    N      69835.1699     61766.1953       7.8145         .1449
AMMONIA                       272.1552    N         98.9812        82.4698       4.3696         .9821
DISSOLVED SOLIDS           213188.2383    N     111935.8633     39127.6113       4.5693         .9952


****************************************************
 SOURCE EXPECTED DAMAGE                     9.1068
 SOURCE PROBABILITY OF NO VIOLATION          .0218
****************************************************



                                          ************
                                           SOURCE 19
                                          ************

PIPE= 1         MEAN DISCHARGE (ML/DAY)=        .1330          UPSTREAM FLOW (ML/DAY)=       4.8937

                                                                                EXPECTED   PROB. OF NO
     CONSTITUENT             STANDARD    DIST   EST. MEAN      EST. SIGMA        DAMAGE     VIOLATION
-------------------      -------------   ----  ------------   ------------     --------   -----------
SUSPENDED SOLIDS              123.0225    L           .4025          .8625        .2858         .9748
CHLOROFORM EXTRACT             73.8135    L          -.2913          .3790       3.8226        1.0000


****************************************************
 SOURCE EXPECTED DAMAGE                     3.8226
 SOURCE PROBABILITY OF NO VIOLATION          .9748
****************************************************
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                                        ************
                                         SOURCE 20
                                        ************

PIPE= 1          MEAN DISCHARGE (ML/DAY)=        .8176          UPSTREAM FLOW (ML/DAY)=    195.7500

                                                                                  EXPECTED    PROB. OF NO
     CONSTITUENT               STANDARD     DIST    EST. MEAN       EST. SIGMA     DAMAGE      VIOLATION
--------------------        ------------    ----   ------------   ------------    --------    -----------
PH-MAX                            9.5000     N           6.6901          .5338    ********    ***********
PH-MIN                            6.5000     N           6.6613          .4555       .0161          .6384
SUSPENDED SOLIDS                 49.8725     N          33.5698        22.4706       .0174          .7659
PHOSPHORUS                        9.9745     N           6.4118         7.5453       .7368          .6816


*****************************************************
 SOURCE EXPECTED DAMAGE                      .7368
 SOURCE PROBABILITY OF NO VIOLATION          .3333
*****************************************************




                                        ************
                                         SOURCE 22
                                        ************

PIPE= 1          MEAN DISCHARGE (ML/DAY)=     40.7535           UPSTREAM FLOW (ML/DAY)=    203.0900
  MEAN DO CONCENTRATION (MG/L)=       4.3690

                                                                                  EXPECTED    PROB. OF NO
     CONSTITUENT               STANDARD     DIST    EST. MEAN       EST. SIGMA     DAMAGE      VIOLATION
--------------------        ------------    ----   ------------   ------------    --------    -----------
BOD5                           1360.7760     N        1537.6694      1462.6501      5.3891          .4519
SUSPENDED SOLIDS                907.1840     L           2.9206          .5022       .6357          .5294
PHOSPHORUS                      378.5300     L           1.6472          .4858      3.6289          .9723


*****************************************************
 SOURCE EXPECTED DAMAGE                     5.3891
 SOURCE PROBABILITY OF NO VIOLATION          .2326
*****************************************************
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```
                                            ***********
                                            SOURCE 23
                                            ***********
PIPE= 1         MEAN DISCHARGE (ML/DAY)=        .4251         UPSTREAM FLOW (ML/DAY)=      14.9260

     CONSTITUENT             STANDARD     DIST    EST. MEAN     EST. SIGMA    EXPECTED    PROB. OF NO
                                                                               DAMAGE      VIOLATION
--------------------      ------------    ----   -----------   ------------   --------    -----------
BOD5                          184.1583     N         64.2895        29.6657     3.8687         1.0000
SUSPENDED SOLIDS              104.7798     N         42.5845        22.5484      .2791          .9971
PHOSPHORUS                      4.3152     N          4.6613         1.3021     4.6290          .3952


**************************************************
 SOURCE EXPECTED DAMAGE                     4.6290
 SOURCE PROBABILITY OF NO VIOLATION          .3940
**************************************************



                                            ***********
                                            SOURCE 24
                                            ***********
PIPE= 1         MEAN DISCHARGE (ML/DAY)=       3.0492         UPSTREAM FLOW (ML/DAY)=     269.1600

     CONSTITUENT             STANDARD     DIST    EST. MEAN     EST. SIGMA    EXPECTED    PROB. OF NO
                                                                               DAMAGE      VIOLATION
--------------------      ------------    ----   -----------   ------------   --------    -----------
BOD5                          408.2328     N        196.4388        68.8322      .9234          .9990
SUSPENDED SOLIDS              272.1552     N        139.3360        92.8147      .0522          .9238


**************************************************
 SOURCE EXPECTED DAMAGE                      .9234
 SOURCE PROBABILITY OF NO VIOLATION          .9228
**************************************************
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                                                  ************
                                                   SOURCE 25
                                                  ************
PIPE= 1        MEAN DISCHARGE (ML/DAY)=    164.9721            UPSTREAM FLOW (ML/DAY)=   1827.8000

     CONSTITUENT               STANDARD     DIST    EST. MEAN       EST. SIGMA    EXPECTED    PROB. OF NO
--------------------         ------------   ----  ------------    ------------    DAMAGE      VIOLATION
BOD5                            4535.9200     N      5085.6584       2481.7704    --------   -----------
SUSPENDED SOLIDS                3628.7360     L         3.7497           .2959      3.5719         .4123
                                                                                     .3556         .2605


*************************************************
 SOURCE EXPECTED DAMAGE                     3.5719
 SOURCE PROBABILITY OF NO VIOLATION          .1074
*************************************************


                                                  ************
                                                   SOURCE 26
                                                  ************
PIPE= 1          MEAN DISCHARGE (ML/DAY)=          7.1535       UPSTREAM FLOW (ML/DAY)=   1862.1000
  MEAN DO CONCENTRATION (MG/L)=          5.9653

     CONSTITUENT               STANDARD     DIST    EST. MEAN       EST. SIGMA    EXPECTED    PROB. OF NO
--------------------         ------------   ----  ------------    ------------    DAMAGE      VIOLATION
BOD5                             278.9591     L         2.0957           .4399    --------   -----------
SUSPENDED SOLIDS                 302.0923     L         2.2366           .3561       .1345         .7848
PHOSPHORUS                        72.2990     N        43.0084         32.3824       .0129         .7530
                                                                                     .4750         .8171


*************************************************
 SOURCE EXPECTED DAMAGE                      .4750
 SOURCE PROBABILITY OF NO VIOLATION          .4841
*************************************************
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                                                  ***********
                                                   SOURCE 27
                                                  ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=      5.5699          UPSTREAM FLOW (ML/DAY)=    349.9000

    CONSTITUENT                  STANDARD     DIST     EST. MEAN      EST. SIGMA    EXPECTED    PROB. OF NO
-------------------          -------------    ----   ------------   ------------    DAMAGE      VIOLATION
BOD5                              272.1552      N       3603.6948       817.3354    --------    -----------
SUSPENDED SOLIDS                  272.1552      N       3382.8377      1500.1360     6.5243          .0000
PHOSPHORUS                         58.2940      N        311.0573        64.9729      .9534          .0191
                                                                                     6.6753          .0001


**************************************************
 SOURCE EXPECTED DAMAGE                    6.6753
 SOURCE PROBABILITY OF NO VIOLATION         .0000
**************************************************




                                                  ***********
                                                   SOURCE 28
                                                  ***********

PIPE= 1          MEAN DISCHARGE (ML/DAY)=    110.8503          UPSTREAM FLOW (ML/DAY)=    266.7100
  MEAN DO CONCENTRATION (MG/L)=     4.8551

    CONSTITUENT                  STANDARD     DIST     EST. MEAN      EST. SIGMA    EXPECTED    PROB. OF NO
-------------------          -------------    ----   ------------   ------------    DAMAGE      VIOLATION
BOD5                             4989.5120      N       1413.0719       845.8808    --------    -----------
SUSPENDED SOLIDS                 4082.3280      N       3151.0186      2321.0495     4.6933         1.0000
PHOSPHORUS                        529.9500      N        301.2218       148.7913      .8593          .6559
                                                                                     6.2030          .9379


**************************************************
 SOURCE EXPECTED DAMAGE                    6.2030
 SOURCE PROBABILITY OF NO VIOLATION         .6151
**************************************************
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                                            ************
                                             SOURCE 29
                                            ************

PIPE= 1          MEAN DISCHARGE (ML/DAY)=       4.1106            UPSTREAM FLOW (ML/DAY)=     12.2340

                                                                                   EXPECTED   PROB. OF NO
     CONSTITUENT                STANDARD     DIST    EST. MEAN        EST. SIGMA     DAMAGE     VIOLATION
--------------------          ------------   ----   ------------    ------------   --------   -----------
BOD5                              170.0970    N          93.4627         77.9805     6.5963         .8371
SUSPENDED SOLIDS                  170.0970    L           1.7007           .3274      .4079         .9473


**************************************************
 SOURCE EXPECTED DAMAGE                     6.5963
 SOURCE PROBABILITY OF NO VIOLATION          .7930
**************************************************
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                                            ************
                                             SOURCE 30
                                            ************

PIPE= 1          MEAN DISCHARGE (ML/DAY)=      35.0425            UPSTREAM FLOW (ML/DAY)=   1862.1000

                                                                                   EXPECTED   PROB. OF NO
     CONSTITUENT                STANDARD     DIST    EST. MEAN        EST. SIGMA     DAMAGE     VIOLATION
--------------------          ------------   ----   ------------    ------------   --------   -----------
BOD5                             1587.5720    N        1625.9873        759.3214     1.1913         .4798
SUSPENDED SOLIDS                 1360.7760    N        1654.7131        720.3438      .0874         .3416


**************************************************
 SOURCE EXPECTED DAMAGE                     1.1913
 SOURCE PROBABILITY OF NO VIOLATION          .1639
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